AD-A119 550   NAVAL FACILITIES ENGINEERING COMMAND ALEXANDRIA VA   F/G 13/2
COASTAL SEDIMENTATION AND DREDGING. DESIGN MANUAL 26.3.(U)
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UNCLASSIFIED   NAVFAC-DM-26.3   NL

1 OF 1
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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
DM-26.3

2. GOVT ACCESSION NO.
AD-A119 550

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
NAVFAC Design Manual DM- 26.3
Coastal Sedimentation and Dredging

5. TYPE OF REPORT & PERIOD COVERED
Design Criteria
Final

6. PERFORMING ORG. REPORT NUMBER
DM-26.3

7. AUTHOR(s)
Naval Facilities Engineering Command
200 Stovall Street
Alexandria, VA 22332 (Code 0453)

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Naval Facilities Engineering Command
200 Stovall Street
Alexandria, VA 22332

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
Engineering and Design

11. CONTROLLING OFFICE NAME AND ADDRESS
Naval Facilities Engineering Command (Code 0432)
200 Stovall Street
Alexandria, VA 22332

12. REPORT DATE
December 1981

13. NUMBER OF PAGES
69

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)
Unclassified/Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)
Unclassified/Unlimited

18. SUPPLEMENTARY NOTES

A

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
Dredging; dredging economics; dredging equipment; harbor siting; sedimentation and erosion; shore protection.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)
Design and planning guidelines are presented for the layout of harbors where coastal and estuarine sedimentation are factors. Section 1 is an introduction. Section 2 includes basic principles of sedimentation, harbor siting, and shore protection. Section 3 gives planning considerations for dredging works and discusses general dredge types.

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DECEMBER 1981
NAVFAC DM-26.3

Coastal Sedimentation and Dredging

DESIGN MANUAL 26.3

APPROVED FOR PUBLIC RELEASE

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ABSTRACT

Design and planning guidelines are presented for the layout of harbors where coastal and estuarine sedimentation are factors. Section 1 is an introduction. Section 2 includes basic principles of sedimentation, harbor siting, and shore protection. Section 3 gives planning considerations for dredging works and discusses general dredge types.

FOREWORD

This design manual is one of a series developed from an evaluation of facilities in the shore establishment, from surveys of the availability of new materials and construction methods, and from selection of the best design practices of the Naval Facilities Engineering Command, other Government agencies, and the private sector. This manual uses, to the maximum extent feasible, national professional society, association, and institute standards in accordance with NAVFACENGCOM policy. Deviations from these criteria should not be made without prior approval of NAVFACENGCOM Headquarters (Code 04).

Design cannot remain static any more than can the naval functions it serves or the technologies it uses. Accordingly, recommendations for improvement are encouraged from within the Navy and from the private sector and should be furnished to NAVFACENGCOM Headquarters (Code 04). As the design manuals are revised, they are being restructured. A chapter or a combination of chapters will be issued as a separate design manual for ready reference to specific criteria.

This publication is certified as an official publication of the Naval Facilities Engineering Command and has been reviewed and approved in accordance with SECNAVINST 5600.16.

W. M. Zobel
Rear Admiral, CEC, U. S. Navy
Commander
Naval Facilities Engineering Command

HARBOR AND COASTAL FACILITIES DESIGN MANUALS

DM Number	Superseded Chapter in Basic DM-26	Title
26.1	1, 4	Harbors
26.2	2	Coastal Protection
26.3	1, 2, 3	Coastal Sedimentation and Dredging
26.4	5	Fixed Moorings
26.5	6	Fleet Moorings
26.6	7	Mooring Design Physical and Empirical Data

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COASTAL SEDIMENTATION AND DREDGING

Section 1. INTRODUCTION

1. SCOPE. This manual presents general phenomena involved in and planning guidelines for the construction of harbors in regions prone to coastal and estuarine sedimentation problems. Discussed are basic principles of sedimentation, harbor siting, and shore protection, along with planning considerations for dredging works. General dredge types are also described.

2. CANCELLATION. This manual, NAVFAC DM-26.3, Coastal Sedimentation and Dredging, cancels and supersedes Chapter 3 and portions of Chapters 1 and 2 of the basic Design Manual 26, Harbor and Coastal Facilities, dated July 1968, and Change 1, dated December 1968.

3. RELATED CRITERIA. Certain criteria related to coastal sedimentation and dredging appear elsewhere in the design manual series. See the following sources:

Subject	Source
Coastal Sedimentation	
Coastal protection	DM-26.2
Harbors	DM-26.1
Pollution control	DM-5.8
Soil mechanics	DM-7
Dredging	
Dredges and dredge capabilities	DM-38
Dredging records	DM-6
Geometric requirements	DM-26.1
Hydrographic surveys	DM-5
Jurisdiction over navigable waters	DM-26.1
Subsoil exploration	DM-7

4. COLLATERAL READING.

(1) Shore Protection Manual, U.S. Army Coastal Engineering Research Center, 3d ed., Vols. I, II, and III, Stock No. 008-022-00113-1, U.S. Government Printing Office, Washington, D.C., 1977.

(2) Vanoni, V.A., Editor; Sedimentation Engineering, ASCE, Manuals and Reports on Engineering Practice, No. 54, Prepared by the ASCE Task Committee for the Preparation of the Manual on Sedimentation of the Sedimentation Committee of the Hydraulics Division, American Society of Civil Engineers, New York, NY, 1977.

(3) Wicker, C.F.; Evaluation of Present State of Knowledge of Factors Affecting Tidal Hydraulics and Related Phenomena, Report No. 3, Committee on Tidal Hydraulics, Corps of Engineers, U.S. Army, Vicksburg, MS, May 1965.

Section 2. COASTAL SEDIMENTATION AND EROSION

1. GENERAL. This section addresses general concepts of coastal sedimentation and erosion and their application to design and construction in coastal areas. Soil classification, transport potential, littoral processes, the siting of harbors on open, sandy coasts, in inlets, and in estuaries, as well as shore protection, are discussed.

2. BASIC CONSIDERATIONS. Sediment transport and deposition occur on open coasts, in tidal inlets, in estuaries, in harbors, and in rivers. The types of sedimendation problems that occur at each of these locations depend on the soil type, continuity of materials, and the potential for fluid motion to transport the material. Soil classification, the principle of continuity, and an analysis of transport potential are presented in the following subsections.

a. Soil Classification. Sediments can be classified as cohesionless or cohesive. Cohesionless sediments include boulders, cobbles, gravel, sand, and some silts. They generally are found on open coasts, in tidal inlets, and in upper reaches of fluvial channels where there is high-velocity flow.

Cohesive sediments include some silts, clays, and organic materials. These sediments are generally found in estuaries, harbors, and rivers, or where lower-velocity flow is prevalent. Cohesive sediments bind together b molecular forces and deform plastically. In estuaries, suspended clay particles bind with one another to form a larger mass which eventually can settle as a group.

Table 1 gives a classification of soils according to grain size. Two methods of classification are provided: the Wentworth Scale and the Unified Soil Classification. The Wentworth Scale is based on a phi-unit (ϕ) scale, where phi units are defined as:

$$\phi = -\log_2 d \qquad (2\text{-}1)$$

WHERE: d = grain diameter, in millimeters

The Unified Soil Classification is based on U.S. Standard Sieve sizes. In engineering practice, it is common to classify the sediment by its median grain size. The median grain size is the size in millimeters that divides the sediment sample so that half the sample, by weight, has particles coarser than that size.

b. Continuity. The principle of continuity of sediments is basic to sedimentation problems. Continuity accounts for the conservation of sediment materials throughout a region of study in a given time period. Given a control volume as shown in Figure 1, the outflux, Q_{out}, of material moving out of the control volume must equal the influx, Q_{in}, minus the amount stored, $+Q_{stored}$, or eroded, $-Q_{stored}$. If the Q_{in} equals Q_{out}, then a stability is achieved and the control volume contains a constant amount of material. This state of stability is referred to as a "dynamic equilibrium." Examples of dynamic equilibria are a beach of constant width and a channel of constant cross section. On the other hand, if material is stored, the

TABLE 1
Grain-Size Scales for Soil Classification

Wentworth Scale (Size Description)		Phi Units ${}^{1}\phi$	Grain Diameter d (mm)	U.S. Standard Sieve Size	Unified Soil Classification (USC)	
Boulder						
		-8	256		Cobble	
Cobble			76.2	3 in		
		-6	64.0		Coarse	Gravel
Pebble			19.0	3/4 in		Gravel
Pebble			4.76	No. 4	Fine	Gravel
		-2	4.0		Coarse	Sand
Granule		-1	2.0	No. 10		Sand
Sand	Very Coarse	0	1.0		Medium	Sand
Sand	Coarse	1	0.5		Medium	Sand
Sand	Medium		0.42	No. 40		Sand
Sand		2	0.25		Fine	Sand
Sand	Fine	3	0.125		Fine	Sand
Sand	Very Fine		0.074	No. 200		
		4	0.0625		Silt or Clay	
Silt		8	0.00391		Silt or Clay	
Clay		12	0.00024		Silt or Clay	
Colloid						

[1] $\phi = -\log_2 d$, where d = diameter, in millimeters

(SHORE PROTECTION MANUAL, 1977)

beach accretes or the channel section decreases. If material is eroded, the beach decreases in width or the channel section increases.

A balance of material must always be accounted for in all analyses of sediments within a control volume. Sources and sinks may exist, which must be accounted for in the balance of material. A source is defined as any process that increases the quantity of sediment in a defined control volume. Examples of sources are: rivers, streams, discharge of dredged materials, discharge of human and industrial wastes, and erosion of dunes and cliffs. A sink is defined as any process that decreases the quantity of sediment in a defined control volume. Examples of sinks are: submarine canyons, inlets, offshore sand transport, and removal of dredge material. When considering sources and sinks, one must consider the potential transport of material in and out of the control volume. However, when the principle of continuity is invoked, it is the difference of transport into and out of the control volume that is important, not the absolute values.

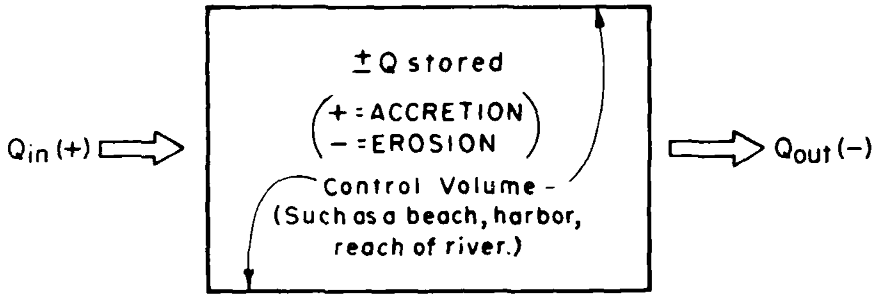
c. Transport Potential. Transport potential is the amount of material that a flow of water can move provided there is material available to be moved. The principle of continuity must be invoked to ensure that the material for transport is available. The transport rate is the actual amount of material moved per unit time into or out of the control volume. Transport results because a flow of water over a bed of sediment produces a tractive force on the sediment which acts to dislodge and move the sediment particles. The transport rate is a function of the material type, material availability, and power available in the flow to move the material. In general, it is the weight of cohesionless particles which resists the tractive force produced by the flowing fluid. On the other hand, sediments which contain significant fractions of cohesive soils resist the tractive force more by cohesion than by weight. Tractive forces include wind, stream flow, waves and wave-induced currents, tidal-induced currents in inlets, and estuarine flows (these include density currents, tidal currents, and currents which result from reversing flows in curved sections of the estuary and Coriolis forces induced by the earth's rotation). These mechanisms will be discussed in subsequent paragraphs.

Movement of sediment by water generally falls into two basic categories: bedload and suspended load. Bedload is moved along the bottom by rolling and bouncing motions. Suspended load is material suspended in the water column by the turbulence of the water motion. For a given flow condition, fine, cohesionless material is more likely to be carried in suspension than a coarse, cohesionless or a cohesive material.

(1) Initiation of Motion of Cohesionless Sediments. The initiation of motion of cohesionless bed sediments has been related to bed shear stress or tractive force under steady, uniform-flow conditions. The bed shear stress, τ_o, is defined as follows:

$$\tau_o = \gamma_w R S \tag{2-2}$$

WHERE: τ_o = bed shear stress, in pounds per square foot



WHERE: Q = volume of sediment transported per unit time

Q_{in} = influx

Q_{out} = outflux

$+Q_{stored}$ = deposition or accretion

$-Q_{stored}$ = scouring or erosion

IF $Q_{in} > Q_{out}$, sediment will deposit or accrete in control volume

IF $Q_{in} < Q_{out}$, sediment will be scoured or eroded from control volume

IF $Q_{in} = Q_{out}$, the control volume is in a state of dynamic equilibrium

FIGURE 1
Control-Volume Approach to Sediment Continuity

γ_w = unit weight of water, in pounds per cubic foot

R = hydraulic radius of channel, in feet (R is equal to channel depth, d_c, for a very wide channel)

S = channel slope

The bed shear stress, τ_o, may be related to the mean channel velocity, $\bar{V}$, as follows:

$$\bar{V} = \sqrt{C_h \frac{\tau_o}{\gamma_w}} \tag{2-3}$$

WHERE: $\bar{V}$ = mean channel velocity, in feet per second

C_h = Chezy coefficient

τ_o = bed shear stress, in pounds per square foot

γ_w = unit weight of water, in pounds per cubic foot

The bed shear stress on a cohesionless sediment of given size increases as the flow velocity increases. A critical point is reached at which the bed shear stress is sufficient to induce motion of the cohesionless particle. Once the sediment has started to move, sediment motion can be sustained by water velocities that are only 80 percent of the value required to induce motion. Figure 2, known as Shields diagram, is used to predict whether a given bed shear stress is sufficient to move a given bed sediment. Figure 2 is a graph of the dimensionless bed shear stress, τ_*, versus the boundary layer Reynolds number, R_*. These two parameters, τ_* and R_*, are defined as follows:

$$\tau_* = \frac{\tau_o}{(\gamma_s - \gamma_w)\ d_s} \tag{2-4}$$

WHERE: τ_* = dimensionless bed shear stress

τ_o = bed shear stress as defined by Equation (2-2), in pounds per square foot

γ_s = unit weight of bed sediment, in pounds per cubic foot

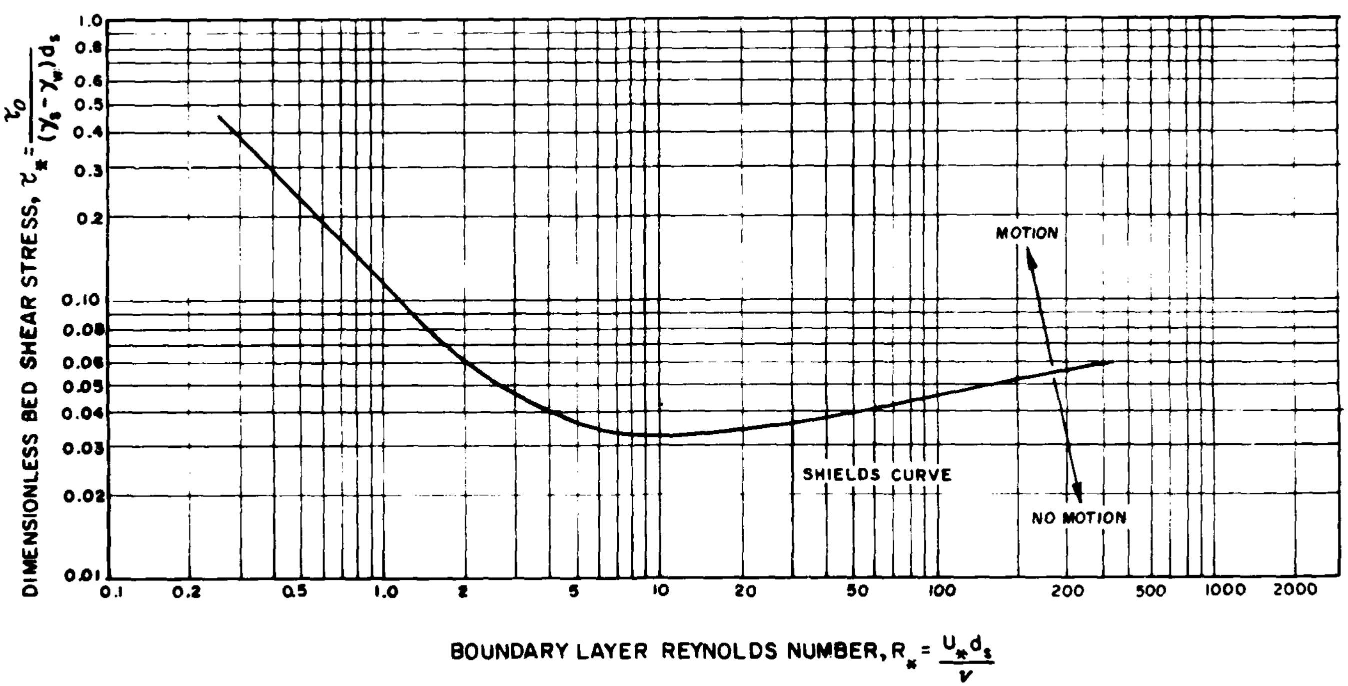
γ_w = unit weight of water, in pounds per cubic foot

d_s = diameter of bed sediment, in feet

$$R_* = \frac{U_*\ d_s}{\nu} \tag{2-5}$$

WHERE: R_* = boundary layer Reynolds number

$U_* = \sqrt{\tau_o/\rho}$ = shear velocity, in feet per second



(AFTER VANONI, 1977)

FIGURE 2
Shields Diagram: Dimensionless Bed Shear Stress Versus the Boundary Layer Reynolds Number

ρ = density of water, in slugs per cubic foot

d_s = diameter of bed sediment, in feet

ν = kinematic viscosity of water, in square feet per second

Also plotted on Figure 2 is the Shields curve, which separates the regions of motion and no motion for cohesionless sediments.

The use of Figure 2 is illustrated in the example which follows.

EXAMPLE PROBLEM 1

Given:
a. A channel with hydraulic radius R = 5 feet
b. Channel slope, S = 0.00015
c. Diameter of bed sediment, d_s = 0.003 feet
d. Unit weight of water, γ_w = 62.4 pounds per cubic foot
e. Unit weight of bed sediment, γ_s = 165 pounds per cubic foot
f. Kinematic viscosity of water, ν = 1.08×10^{-5} square feet per second
g. Density of water, ρ = 1.94 slugs per cubic foot

Find: Determine whether sediment will move.

Solution: (1) Using Equation (2-2), find τ_o;

$$\tau_o = \gamma_w R S$$

$$\tau_o = (62.4)(5)(0.00015)$$

$$\tau_o = 0.0468 \text{ pounds per square foot}$$

(2) Using Equation (2-5), find R_*:

$$R_* = \frac{U_* d_s}{\nu}$$

WHERE: $U_* = \sqrt{\tau_o/\rho} = \sqrt{\frac{0.0468}{1.94}}$ = 0.155 feet per second

$$R_* = \frac{(0.155)\ d_s}{\nu} = \frac{(0.155)(0.003)}{1.08 \times 10^{-5}} = 43.06$$

(3) Using Equation (2-4), find τ_*:

$$\tau_* = \frac{\tau_o}{(\gamma_s - \gamma_w)\ d_s}$$

$$\tau_* = \frac{0.0468}{(165 - 62.4)(0.003)} = 0.152$$

EXAMPLE PROBLEM 1 (Continued)

(4) On Figure 2, find the point of intersection of τ_* and R_*. This point is above the Shields curve for the values of τ_* and R_* determined above; therefore, the sediment will move.

Because of variations in material shape and size, grain-size distribution, and water-flow characteristics, there exist numerous empirical and theoretical relationships between unidirectional stream fluid flow and sediment transport capacity. These relationships have produced scatter in their quantitative predictions of transport; this scatter is indicative of the complexity of the phenomena involved.

(2) Initiation of Motion of Cohesive Sediments. A sediment will have cohesive properties when it contains significant portions of silts and clays. Cohesive sediments are more resistant to bed shear stress than cohesionless soils. The behavior of cohesive sediments under fluid flow is complex and depends not only on the flow regime but also on the electrochemical properties of the sediments. Little is known of the critical bed shear stress required to initiate scour of cohesive sediments, but a preliminary procedure is provided below. Estimates of the critical bed shear stress required to initiate scour of cohesive sediments in canals are given in Figure 3. This figure shows that the critical bed shear stress is a strong function of the void ratio of the sediment and of the sediment type.

The void ratio, e, is defined as follows:

$$e = \frac{V_v}{V_s} \qquad (2\text{-}6)$$

WHERE: e = void ratio

V_v = volume of voids

V_s = volume of solids

The use of Figure 3 is illustrated in the example which follows.

EXAMPLE PROBLEM 2

Given:
a. A channel, with clay bed sediment, with hydraulic radius $R = 5$ feet
b. Channel slope, $S = 0.00015$
c. Void ratio, $e = 0.56$
d. Unit weight of water, $\gamma_w = 62.4$ pounds per cubic foot

Find: Determine whether the sediment bed will erode under the flow condition.

EXAMPLE PROBLEM 2 (Continued)

Solution: (1) Using Equation (2-2), find τ_o:

$$\tau_o = \gamma_w R S$$

$$\tau_o = (62.4)(5)(0.00015)$$

$$\tau_o = 0.0468 \text{ pounds per square foot}$$

(2) From Figure 3 for e = 0.56, it can be seen that this flow condition is not sufficient to erode the bed.

Note: The same flow condition which erodes the cohesionless sediment is not capable of eroding the cohesive sediment.

3. HARBOR SITING. Consideration should be given to sedimentation when siting a harbor on an open-coastal littoral system, in an inlet system, or in a river-mouth estuary system. In each of these systems, the various factors of transport capacity and sediment supply must be taken into account. A natural equilibrium may be evidenced by unchanging channel depths or stable shoreline positions. Conversely, gradual and long-term sedimentation or erosion processes may be occurring.

a. Littoral Processes. Siting a harbor on the shore of any large body of water where wave action is present involves understanding and taking into account littoral processes and their possible effects on the entrance. The continuity relationship for a given length of beach is illustrated in Figure 4.

Littoral transport is the movement of littoral material, such as sand along or across a beach, due to the interaction of wind, waves, and currents with sediments. Littoral transport on a beach differs from that in a river in that, on a beach, oscillatory wave-induced motions play a significant role in initiating sediment-movement force. The turbulence of breaking waves entrains material in the water column, where it is susceptible to transport by currents. Wave action moves sediments up, down, towards, and away from the beach, tending to establish a beach and offshore profile that is in a state of quasi-equilibrium with the forces induced by water motion and gravity. As the incident wave conditions change, the beach profile and plan forms change to a new equilibrium condition. Material can move onshore, offshore, or alongshore, depending on the wave conditions relative to the beach conditions.

Longshore transport is the movement of sediments parallel to the beach. When a wave approaches the shoreline at an oblique angle, longshore currents landward of the breaker line result. These currents, generated by the longshore component of momentum of the fluid entering the surf zone, transport suspended sediments in the alongshore direction. Figure 5 shows the longshore-current velocity profile, which indicates a maximum value at some distance landward of the breaker line. Figure 5 also shows the zigzag transport of material along the beach face. This zigzag pattern results from the

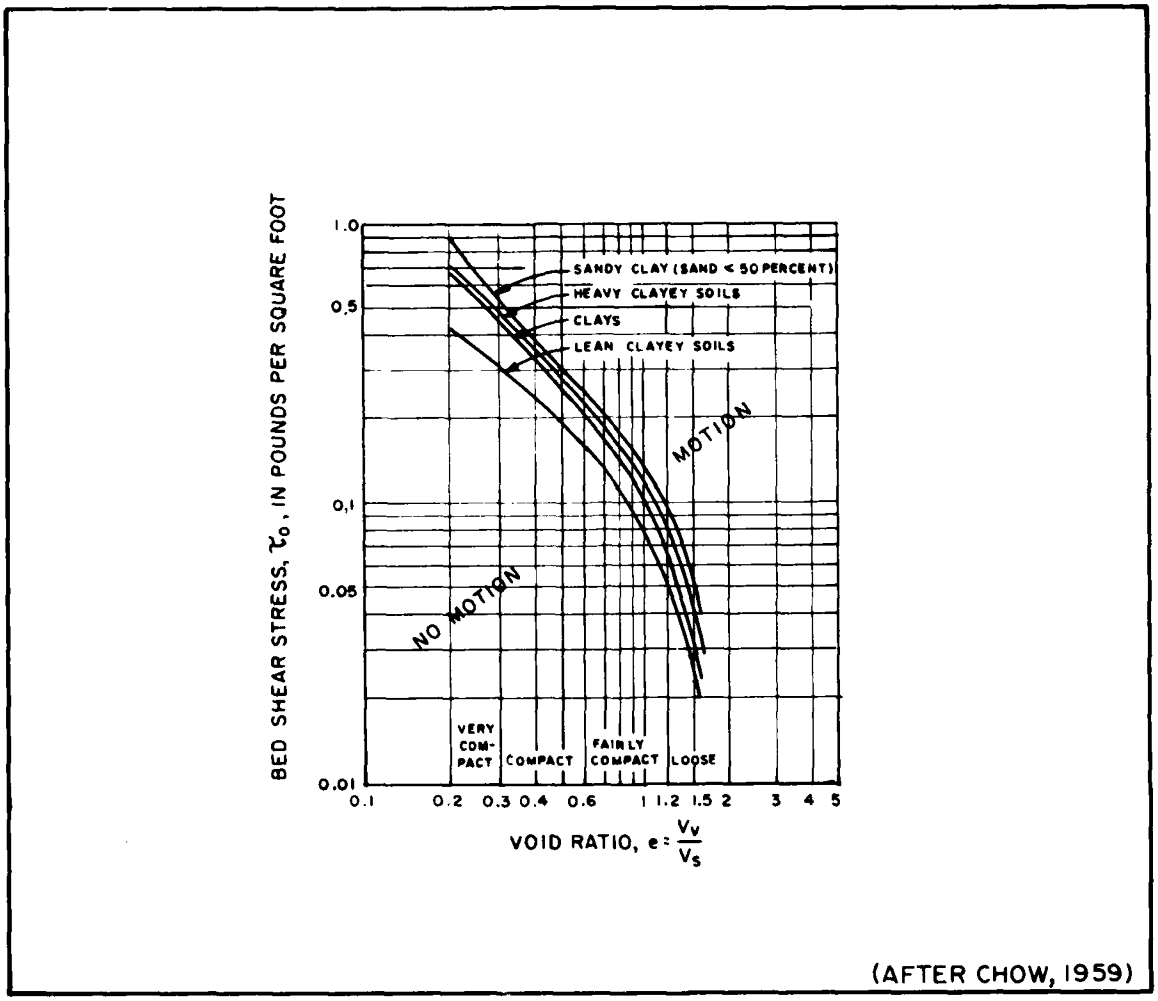


FIGURE 3
Critical Bed Shear Stress Required to
Initiate Scour of Cohesive Sediments in Canals

superposition of the flow of wave uprush on the beach face with the longshore current.

Because longshore transport is a function of the breaking-wave climate, and because the wave climate varies as a function of meteorological events, the longshore transport rate on a beach varies on a daily basis. Wave energy generally arrives from different meteorological sources during different seasons of the year. This seasonal variation in wave energy will change the longshore transport and offshore transport rates and may also change their directions. Hence, the rate and direction of material movement can be characterized by seasons. The term "gross transport" is the absolute value of littoral transport in all directions. The term "net transport" is the difference in littoral transport in each direction both up and down the

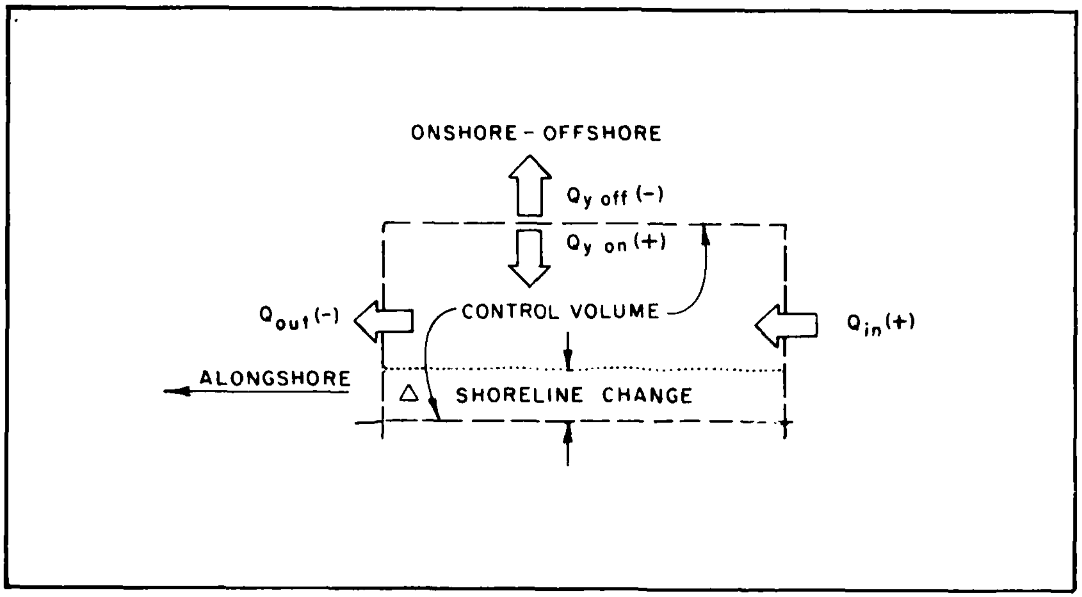


FIGURE 4
Control Volume for a Littoral Transport Budget

coast. The direction of net longshore transport is called the "downdrift" direction and the direction from which material is arriving is called the "updrift" direction. Gross transport material can be trapped in a harbor entrance channel, whereas net transport can accumulate in the area on the updrift side of a jetty and erode from the area on the downdrift side.

Offshore and beach profiles adjust to the incident-wave conditions. High, steep storm waves tend to pull material off the beach and deposit it offshore in a bar. This results in what is often called a storm or winter profile. Low-height, long-period swell tends to move sediment back onto the beach. The result is often called the summer profile. Examples of winter and summer profiles are shown in Figure 6. This adjustment to the seasonal wave climate is one form of onshore and offshore movement. Quantification of this movement is difficult within the present state of knowledge. It is important to note that surveys made in shoreline studies for comparitive purposes should be conducted at the same time of the year.

Another form of onshore and offshore transport is due to a winnowing process whereby material is sorted by wave action. Fine material is carried offshore, while coarse material remains on the beach. This phenomenon can occur during a beach-nourishment project as well as near a river delta which supplies sediment to the beach.

The wind can also transport material onshore, alongshore, or offshore. Fine-grained sands tend to be more susceptible to wind transport. Strong, predominant, onshore winds transport sand shoreward to form sand dunes. Sand can also be transported alongshore to shoal in channels or inlets.

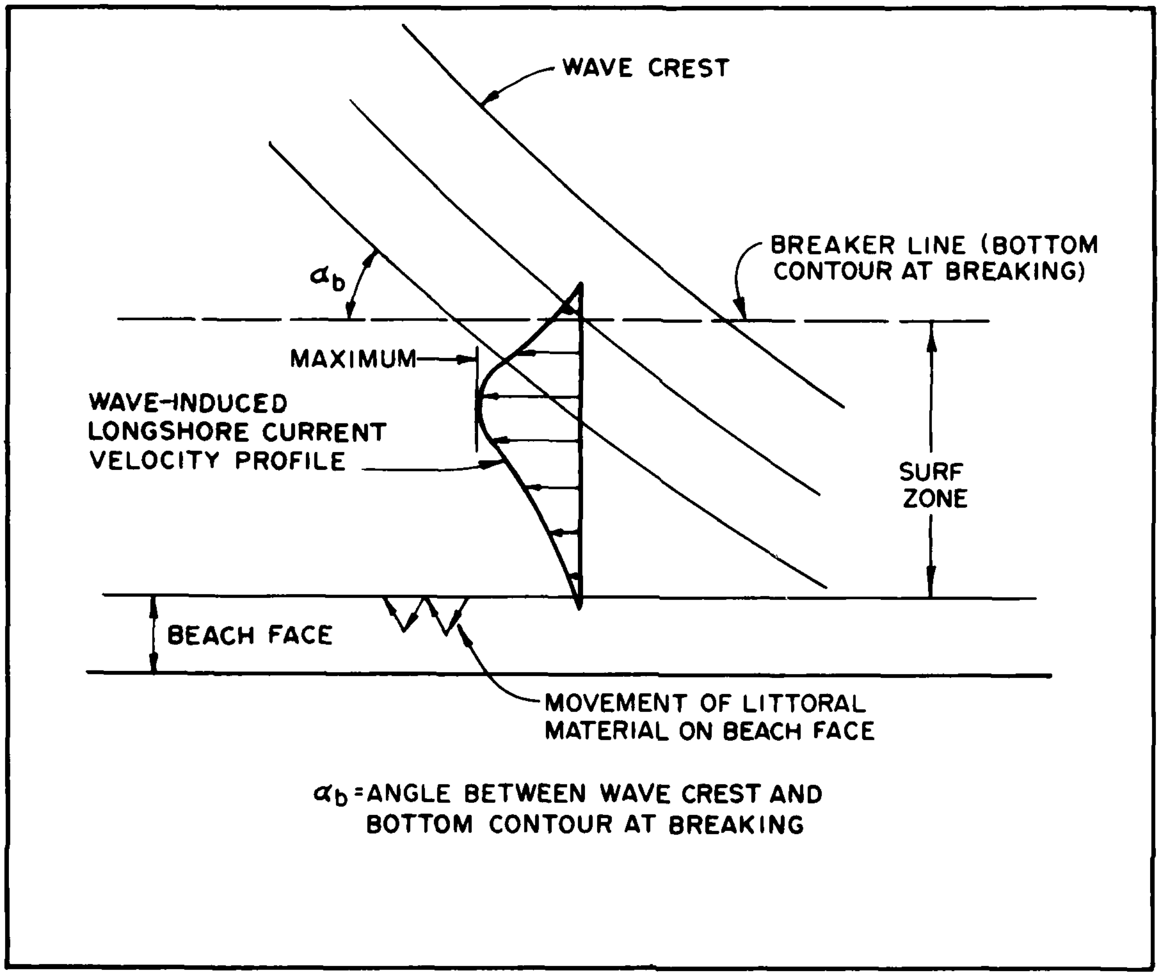


FIGURE 5
Longshore-Current Velocity Profile

(1) Prediction of Longshore Transport. The potential longshore-transport rate on an open coast has been empirically linked to the longshore component of wave-energy flux reaching any given shore segment or control volume. A widely used method of calculating the potential longshore-transport rate, Q, is the SPM formula:

$$Q = K\,P_{ls} \tag{2-7}$$

WHERE: Q = potential longshore-transport rate, in cubic yards per year

K = ... empirical constant (7.5×10^3)

$P_{ls} = \rho \frac{g}{16} H_b^2\, C \sin 2\alpha_b$ = longshore component of wave-energy flux in the surf zone, in foot-pounds per second per foot of shoreline (2-8)

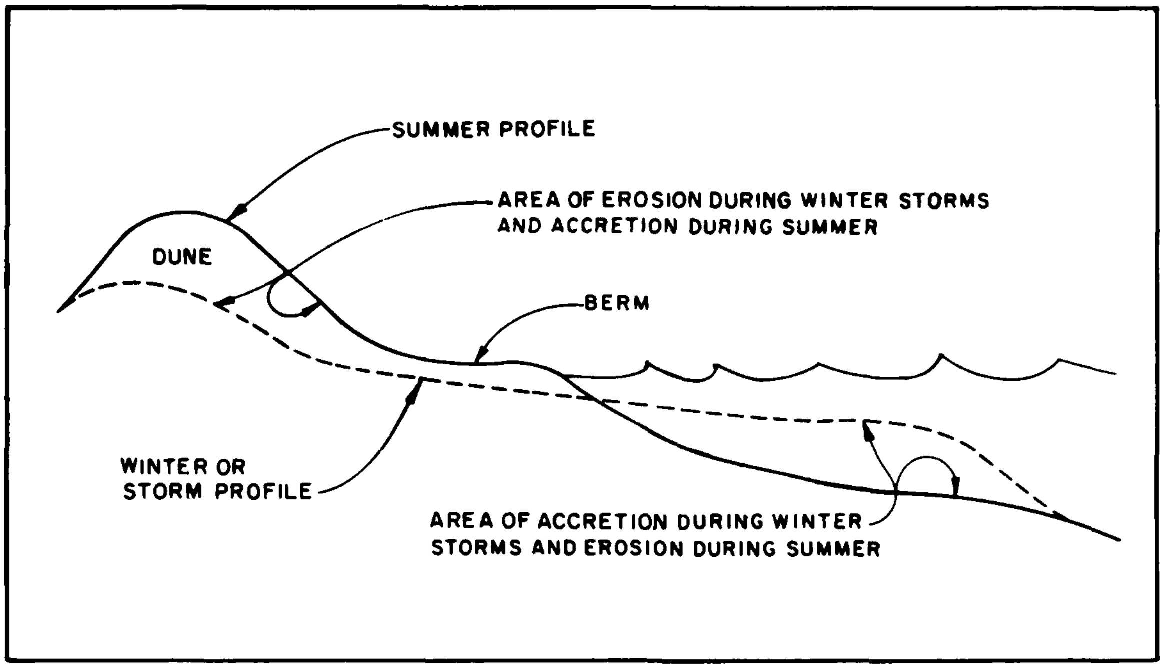


FIGURE 6
Summer and Winter Beach Profiles

ρ = density of water in slugs per cubic foot

g = gravitational acceleration (32.2 feet per second^2)

H_b = wave height at breaking, in feet

C = wave-phase velocity at breaking, in feet per second

α_b = angle between wave crest and bottom contour at breaking

The various parameters are illustrated graphically in Figure 7.

The various steps involved in the prediction of longshore transport are as follows:

(1) Obtain offshore wave data information from sources described in DM-26.2. These data must include a tabulation of incremental wave heights and periods by percent of annual occurrence for each deepwater sector of approach direction.

(2) Prepare refraction diagrams for each wave period and direction tabulated in the offshore wave data and determine refraction effects to a region near the shoreline reach. (See DM-26.2.)

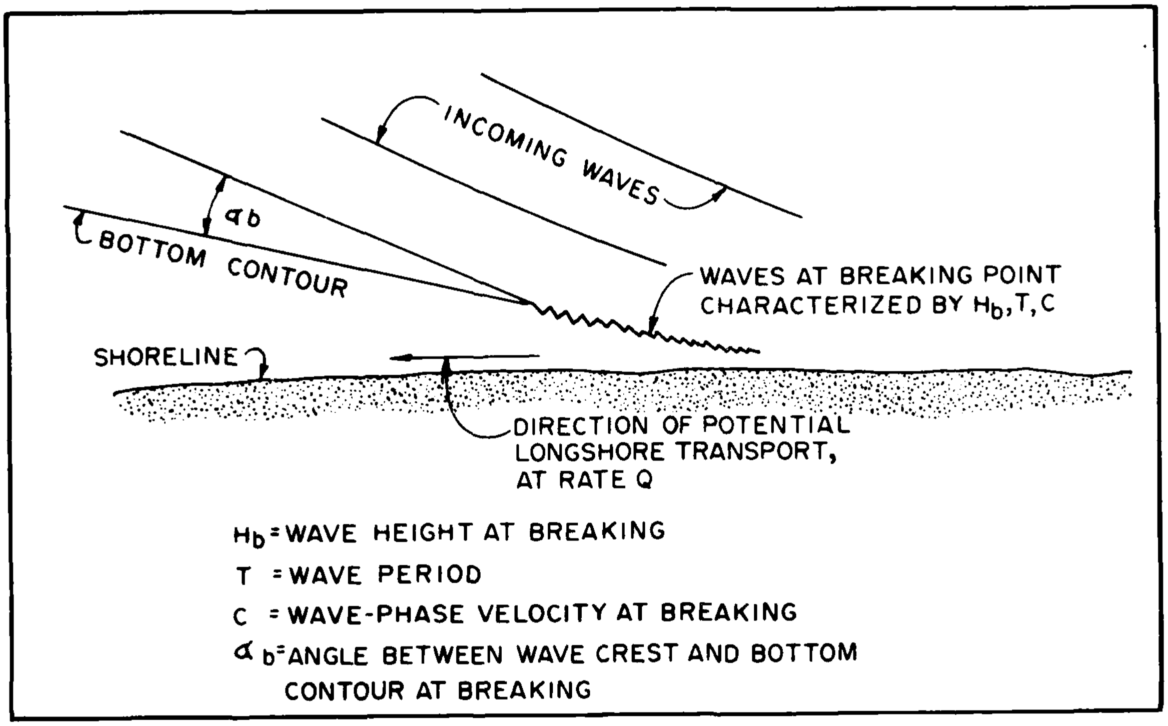


FIGURE 7
Illustration of Parameters Involved in
Calculating Potential Longshore-Transport Rate

(3) Compute breaking-wave height and depth for each offshore wave-height increment. (See DM-26.2.)

(4) Using refraction diagrams, compute the longshore component of energy flux and wave direction at breaking for each wave-height increment.

(5) Compute the gross potential longshore transport rate using each direction, and subtract the smaller (updrift) from the larger (downdrift) value to obtain an estimate of the net potental longshore transport rate in the downdrift direction.

A simplified example of this procedure is given in Example Problem 3.

<u>EXAMPLE PROBLEM 3</u>

<u>Given</u>: a. Breaking-wave height, H_b = 10.0 feet
b. Angle between wave crest and shoreline at breaking, α_b = 45°
c. Wave-phase velocity, C = 20.3 feet per second

EXAMPLE PROBLEM 3 (Continued)

d. Density of water, ρ = 2.0 slugs per cubic foot
e. Gravitational acceleration, g = 32.2 feet per second^2
f. Repeat problem for H_b = 3.0 feet and C = 11 feet per second

Find: The potential longshore-transport rate for the two given wave conditions.

Solution: (1) Using Equation (2-8), find P_{ls}:

$$P_{ls} = \frac{\rho g}{16} H_b^2 \, C \sin 2\alpha_b$$

$$P_{ls} = \frac{(2.0)(32.2)}{16} (10.0)^2 \ (20.3) \sin 2(45°)$$

P_{ls} = 8,170.8 foot-pounds per second per foot

(2) Using Equation (2-7), find Q:

$$Q = K \, P_{ls}$$

$$Q = (7.5 \times 10^3)(8,170.8)$$

$$Q = (7.5 \times 10^3)(8,170.8)$$

Q = 61,281,000 cubic yards per year

Repeat steps (1) and (2) for H_b = 3.0 ft and C = 11:

(1) Using Equation (2-8), find P_{ls}:

$$P_{ls} = \frac{(2.0)(32.2)}{16} (3.0)^2 \ (11) \sin 2(45°)$$

P_{ls} = 398.48 foot-pounds per second per foot

(2) Using Equation (2-7), find Q:

$$Q = (7.5 \times 10^3)(398.48)$$

Q = 2,988,600 cubic yards per year

Note: This value, for the 3-foot breaking-wave height, is approximately 5 percent of that for the 10-foot breaking-wave height. This difference in transport capacity indicates the potential for storm events to move large amounts of material.

(2) Littoral Transport Determined From Historical Shoreline Changes. Determination of the littoral-transport rate from historical records involves review of shoreline changes caused by a discontinuity along a reach of shoreline. Examples of shoreline discontinuities are groins, jetties, tidal inlets, and harbor entrances. Analysis of shoreline changes in the vicinity

of discontinuities may be achieved through analysis of beach surveys, charts, aerial photographs, or records of dredging tidal inlets. Analysis of historical shoreline changes will give a true indication of the transport rate only until the shoreline discontinuity ceases to trap all the material that reaches it. A useful rule of thumb used in the analysis of historical shoreline changes on open coasts is that a loss or gain of 1 square foot of beach area on the berm is equivalent to the loss or gain of 1 cubic yard of beach material from that same area.

(3) Reliability of Predicted Longshore-Transport Rates. The estimates of littoral-transport rates derived by energy-flux calculation or by poorly defined measurements at littoral barriers are approximations. Although analysis of historical shoreline changes may provide a higher level of confidence, underestimation of the transport rate has not been uncommon in past practice. Where accuracy is critical to project development, construction and monitoring of a test groin to verify the estimate should be considered. However, the test groin must extend seaward far enough to trap all the littoral material.

Table 2 provides general estimates of longshore-transport rates at selected U.S. coastal locations. These rates are often modified when additional studies are conducted. The primary source for measured littoral-transport rates is the local District Office of the U.S. Army Corps of Engineers.

b. Harbor Entrances on Open Coasts.

(1) Shoreline Response. Harbors located on or near an open coast often require the construction of a jettied entrance channel. Jetties serve to stabilize the position of the entrance, keep littoral material from entering the navigation channel, modify tidal currents in the channel, and reduce wave action within the channel. The jettied entrance channel will interrupt the natural transport of littoral material alongshore. This is particularly apparent and has adverse effects when there is a predominant direction of longshore transport. Interruption of the longshore transport results in modifications of the shoreline both up- and downdrift of the entrance. Figure 8 (A through C) shows the progression of shoreline response after the construction of a jettied harbor entrance on a coast with a predominant direction of longshore transport. Immediately after construction is completed, the littoral transport across the entrance is completely blocked, as shown in Figure 8A. In time sand accretes, forming a fillet on the updrift side of the entrance. Accompanying this accretion is erosion downdrift of the entrance, resulting from the lack of material supplied from the updrift coast (see Figure 8B.) Eventually, the updrift fillet accretes past the seaward end of the jetty and material forms a shoal in the navigation channel, as shown in Figure 8C. Further erosion downdrift of the entrance may cause property damage. The downdrift erosion may also cause flank erosion, which is erosion past the landward end of the downdrift jetty. The extent and rate of updrift accretion, channel shoaling, and downdrift erosion depend on longshore-transport rate and the hydraulics of the entrance-channel system.

(2) Sand Bypassing at Harbor Entrances. The sedimentation problems associated with harbor entrances on open coasts where there is a predominant

TABLE 2
Longshore-Transport Rates at Selected Coastal Locations

Location	Predominant Direction of Transport	Longshore Transport[1] (cu yd/yr)	Date of Record
Atlantic Coast			
Suffolk County, NY............	W	200,000	1946-55
Sandy Hook, NY...............	N	493,000	1885-1933
Sandy Hook, NY...............	N	436,000	1933-51
Asbury Park, NJ..............	N	200,000	1922-25
Shark River, NJ..............	N	300,000	1947-53
Manasquan, NJ................	N	360,000	1930-31
Barneget Inlet, NJ...........	S	250,000	1939-41
Absecon Inlet, NJ[2]...........	S	400,000	1935-46
Ocean City, NJ[2]..............	S	400,000	1935-46
Cold Spring Inlet, NJ.........	S	200,000	....
Ocean City, MD...............	S	150,000	1934-36
Atlantic Beach, NC...........	E	29,500	1850-1908
Hillsboro Inlet, FL..........	S	75,000	1850-1908
Palm Beach, FL...............	S	150,000-225,000	1925-30
Gulf of Mexico			
Pinellas County, FL..........	S	50,000	1922-50
Perdido Pass, AL.............	W	200,000	1934-53
Pacific Coast			
Santa Barbara, CA............	E	280,000	1932-51
Oxnard Plain Shore, CA........	S	1,000,000	1938-48
Port Hueneme, CA[3]............	S	1,000,000	....
Santa Monica, CA.............	S	270,000	1936-40
El Segundo, CA...............	S	162,000	1936-40
Redondo Beach, CA............	S	30,000	....
Anaheim Bay, CA[2].............	E	150,000	1937-48
Camp Pendleton, CA...........	S	100,000	1950-52
Great Lakes			
Milwaukee County, WI..........	S	8,000	1894-1912
Racine County, WI............	S	40,000	1912-49
Kenosha, WI..................	S	15,000	1872-1909
IL State Line to Waukegan.....	S	90,000	....
Waukegan to Evanston, IL......	S	57,000	....
South of Evanston, IL.........	S	40,000	....
Hawaii			
Waikiki Beach, HI[2]...........	...	10,000	....

[1]Transport rates are estimated net transport rates. In some cases, these approximate the gross transport rates.

[2]Method of measurement is by accretion except for Absecon Inlet, NJ, Ocean City, NJ, and Anaheim Bay, CA, (by erosion) and Waikiki Beach, HI, (by suspended load samples).

[3]Reference for Port Hueneme, CA, is U.S. Army (1980).

(SHORE PROTECTION MANUAL, 1977)

direction of longshore transport are often mitigated by physically transferring littoral material across the entrance in a process referred to as sand bypassing. A properly managed bypassing scheme, incorporating an efficient bypassing system, will provide the needed littoral material to the downdrift beach and will prevent the eventual shoaling of the navigation channel. In general, an investigation of several sand-bypassing systems is necessary to determine the most feasible solution. The possibility of reversals in transport direction needs to be taken into consideration in the investigation. Several sand-bypassing systems are discussed below.

(a) Land-based dredge plant. This system generally consists of dredging the updrift fillet using a clamshell, and trucking the material to the downdrift side. Unlike some of the other systems, this is a mobile system and access throughout the updrift "impoundment" area is often possible. If this system can be employed, all the littoral material may be stopped from reaching the entrance channel. This method can be very effective; however, it becomes cost-prohibitive if long hauling distances are involved.

(b) Fixed hydraulic dredging plant. This method consists of a hydraulic pumping system permanently fixed on the updrift jetty in a region where littoral material is expected to accumulate. The pumping system will pump material from the updrift side and discharge it on the downdrift side. Detailed study of the longshore-transport rate (short-term extremes and average annual rates) is necessary to ensure that the pumping capacity of the system is not exceeded. If the capacity of the pump is exceeded regularly, adequate amounts of sand will not be provided to the downdrift shore. Furthermore, excess accretion on the updrift side may result in loss of material around the seaward end of the jetty. Analysis of littoral processes should also be made to determine the best position for the pumping system along the updrift beach profile and for the discharge pipe on the downdrift beach. If the pumping system is placed too far seaward, it will not pump enough material downdrift. If the pumping system is placed too far landward, sediment may be lost around the jetty. The downdrift discharge pipe must be positioned such that discharged material is not lost offshore or carried back towards the entrance.

(c) Floating Suction or pipeline dredge. This method for bypassing is efficient, but provides high production rates only as long as the dredge is protected from wave activity. With some entrance configurations, a suction dredge can use the entrance structures for wave protection.

(d) Seagoing hopper dredge. A hopper dredge can be used for a bypassing operation. The primary advantage of the hopper dredge is that it can be operated in the open ocean. In general, unless it has pump-out capability, a hopper dredge cannot be used unless it can discharge in an area where the material can be rehandled by another type of dredge.

(e) Jet eductor. An eductor, or jet-pump, system is a recent development in sand-bypassing methods. Clear, high-pressure water is pumped to a nozzle which converts it into a high-velocity, low-pressure jet stream. The suction created by the partial vacuum induced by the jet entrains sand, which is mixed with the water jet and discharged through a pipeline. The sand and water mixture is then pumped to the downdrift beach, aided by a booster

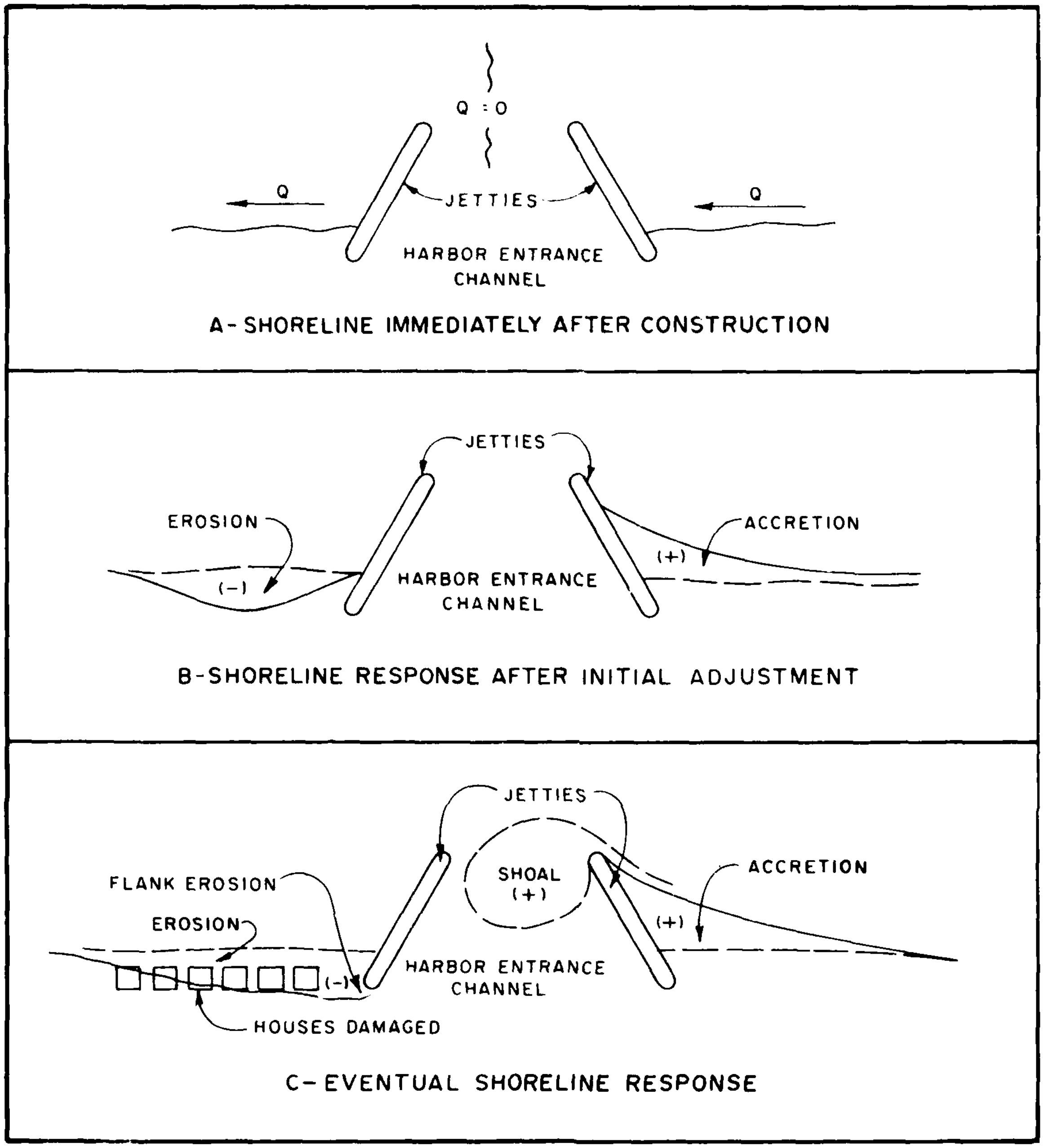


FIGURE 8
Progression of Shoreline Response After
Construction of a Jettied Harbor Entrance on an Open Coast

pump. The basic principle of operation has been to lower an eductor into the sand and allow the eductor to excavate a crater. Wave action and currents theoretically feed the crater. While the system is promising, its effectiveness is not entirely known and it is currently still in a developmental stage.

(3) Entrance Configurations. Figure 9 shows examples of harbor entrance configurations where sand bypassing has been carried out in the past. A discussion of each entrance configuration is given below.

(a) Type I: jettied inlet. This entrance configuration consists of parallel jetties. Land-based or fixed hydraulic dredge plants have been used in conjunction with this configuration in the past. A floating suction dredge can only be used if the impoundment zone is subject to light wave action.

(b) Type II: jettied inlet and offshore breakwater. This entrance configuration consists of a channel protected by two parallel jetties with an offshore breakwater protecting the impoundment zone on the updrift side. The offshore breakwater on the updrift side provides a sheltered region for dredging activities so that a floating suction dredge may be used to transfer material to the downdrift coast in a high energy-wave environment. Furthermore, this system provides an effective means for trapping littoral material on the updrift side of the inlet, which prevents the possibility of shoaling in the entrance. However, the layout of the system is such that none of the material trapped in the lee of the breakwater can be transported updrift during periods of longshore transport reversals. Hence, the system traps the gross longshore transport material, and frequent longshore transport reversals may lead to updrift erosion. A thorough knowledge of the littoral processes and possible longshore transport reversals is necessary for this system to be effectively utilized.

(c) Type III: shore-connected breakwater. This entrance configuration consists of a shore-connected breakwater with an impoundment zone at its seaward end. For this system to be effective, a detailed analysis of the short-term, storm-induced longshore-transport potential is necessary. In this system, sand accumulates at the seaward tip of the breakwater in an area adjacent to the entrance channel. If bypassing operations are not carried out properly and at the correct time intervals, a storm may result in significant shoaling of the entrance channel. This system, like the Type II system, provides a sheltered region in the lee of the seaward end of the breakwater where bypassing may be achieved through the use of a floating suction or hopper dredge. However, waves arriving from critical directions may force a temporary delay in dredging activities. Unlike the Type II system, this system, if properly designed, will allow the movement of littoral material in the upcoast direction during times of longshore-transport reversals.

(d) Type IV: weir jetty. This entrance configuration consists of a weir (or low sill) near the shoreward end of a jetty. This system provides a sheltered impoundment zone where a suction pipe or hopper dredge may be used to transfer littoral material to the downdrift side. A thorough knowledge of littoral processes and entrance-channel hydraulics is necessary for this system to be effectively utilized. This is particularly true if the

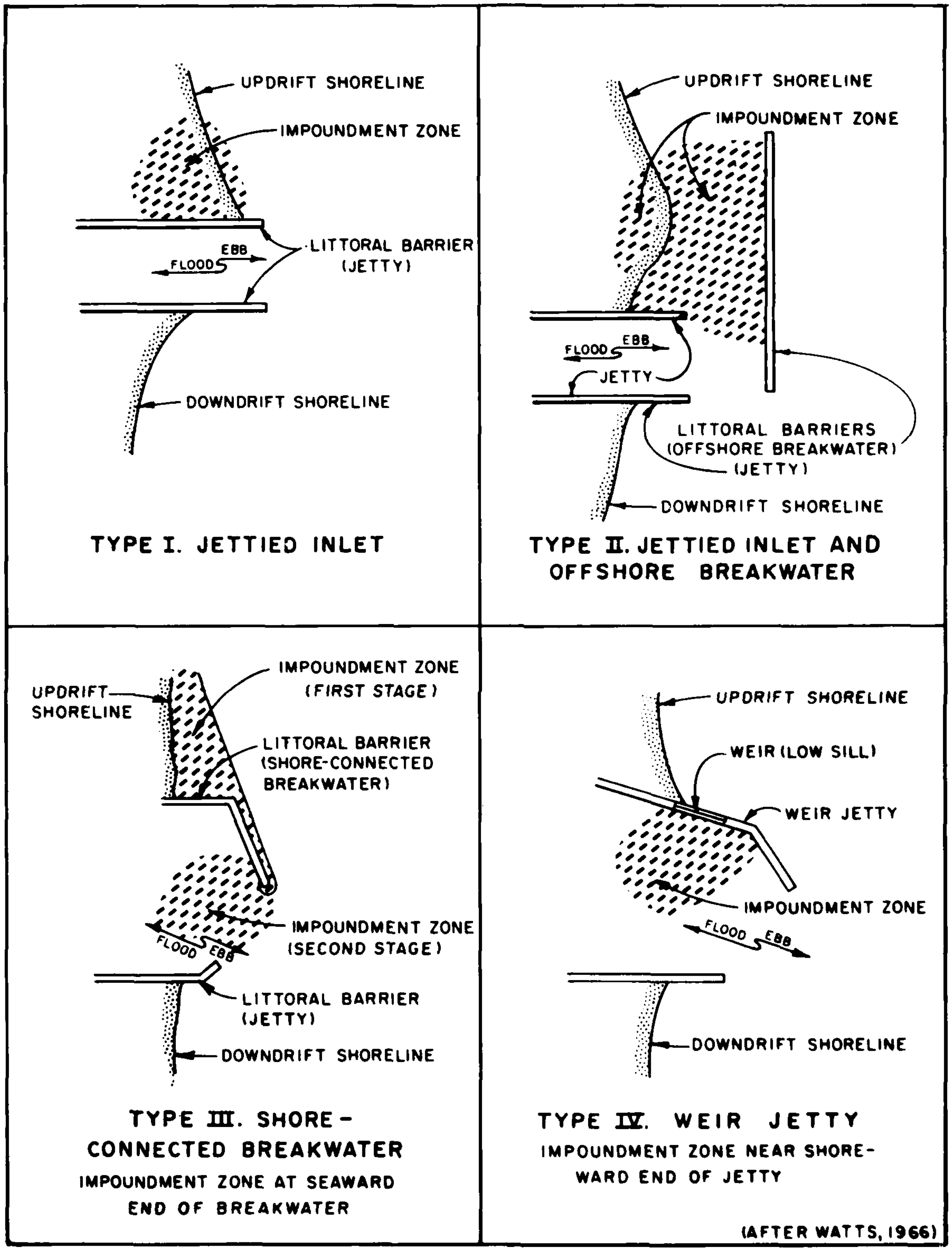


FIGURE 9
Harbor-Entrance Configurations

channel entrance is a natural inlet. (This will be discussed in Subsection 2.3.c., Harbor Entrances Through Natural Inlets.) Currently, a large amount of research is being conducted on wier-jetty systems.

c. Harbor Entrances Through Natural Inlets. Natural inlets on sandy coasts often provide good entrances to sheltered harbor sites inside a bay or lagoon. Tidal currents through the inlet produce a sediment-flushing action which provides a mechanism for the natural transfer of littoral sediments from one side of the entrance to the other. This mechanism may be either of two types, or, in most cases, a combination of both. The two types, bar bypassing and channel bypassing, are shown schematically in Figure 10.

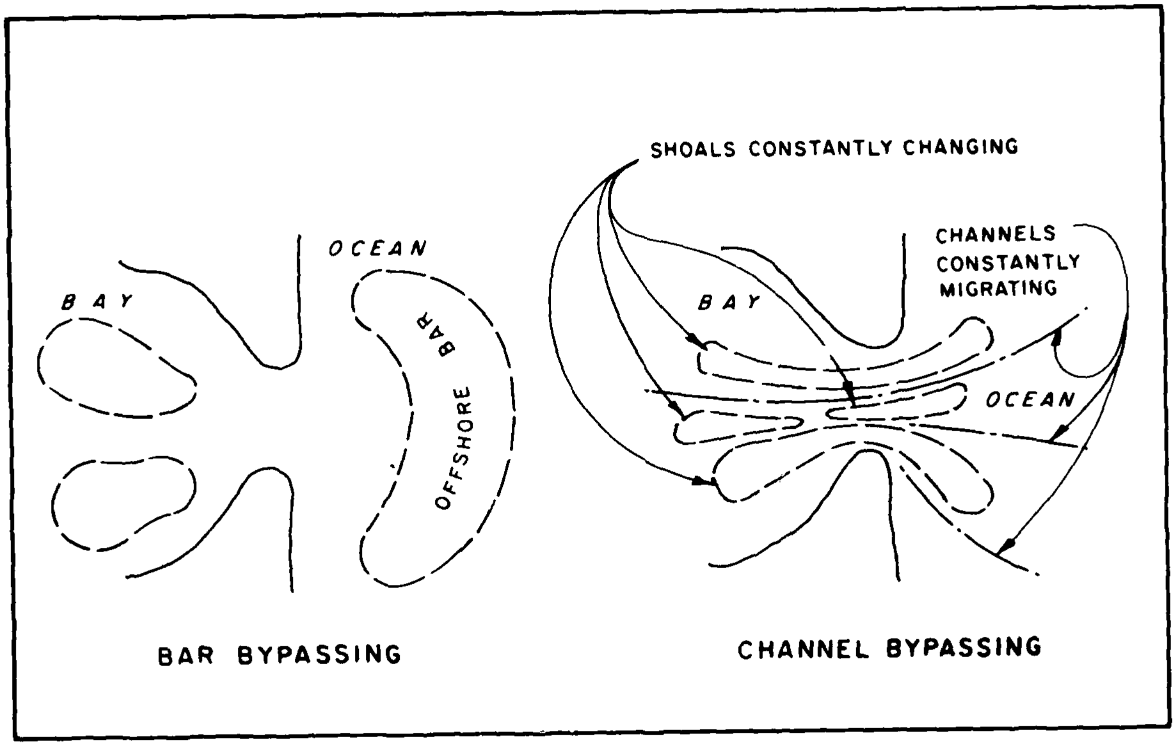


FIGURE 10
Mechanisms of Natural Inlet Bypassing

In bar bypassing, the sediment is transferred by tidal flow and wave-induced longshore transport from the bay side to offshore bars on the ocean side, until the sediment migration across the inlet is completed. The sediments will then proceed downdrift as they did before they reached the channel. With this type of transfer, the throat of the inlet remains deep and fairly stable. Meanwhile, the bars may vary in size and shape, but remain clear of the throat area. In channel bypassing, the sediment is transferred across the inlet through a series of parallel shoals and channels in the inlet

throat. The inlet channels are continually migrating across the inlet mouth as part of the transfer system.

The dominant method of inlet bypassing appears related to the ratio, r, of littoral-transport rate, Q_{mean}, to inlet flushing capacity, $Q_{T_{max}}$. Where the mean littoral-transport rate is high relative to inlet flushing, bar-bypass mechanics dominate; where the littoral-transport rate is low relative to inlet flushing, channel-bypass mechanics dominate. This ratio may be expressed as:

$$r = \frac{Q_{mean}}{Q_{T_{max}}} \tag{2-9}$$

WHERE: Q_{mean} = net longshore-transport rate, in cubic yards per year

$Q_{T_{max}}$ = maximum discharge through the inlet under spring-tide conditions, in cubic yards per second

IF: $r > 200$ to 300, bar bypassing usually prevails

IF: $r < 10$ to 20, channel bypassing usually prevails

In many regions throughout the world, it has been noted that the maximum average velocity, $(\bar{V}_m)_{max}$, measured in the inlet-throat cross section, is relatively constant:

$$(\bar{V}_m)_{max} \simeq 3.3 \text{ feet per second} \tag{2-10}$$

WHERE: $(\bar{V}_m)_{max}$ = maximum average cross-section velocity at maximum tidal flow during spring-tide conditions, in feet per second

The exact value of $(\bar{V}_m)_{max}$ depends on the longshore-transport rate, sediment size, inlet characteristics (width, depth, and bottom friction), and whether or not the inlet is protected by jetties.

Both the sediment-transport capacity of the inlet currents and the longshore sediment-transport rate vary with time; therefore, it is to be expected that, during any given year, the cross-sectional area of the inlet will show variations about the long-term equilibrium value. If short-term variations decrease the cross-sectional area below a certain value, the inlet can conceivably close.

An important factor in evaluating the degree of stability of an inlet (its resistance against closing) is the closure curve shown in Figure 11. The closure curve represents the relationship between the average cross-section velocity, $\bar{V}_m$, at maximum tidal flow during spring-tide conditions, and the cross-sectional area, A_c, both measured in the most restricted reach of the inlet. For relatively short and deep bays, the values of $\bar{V}_m$ may be calculated for different values of A_c from Equation (2-9) in Section 2 of DM-26.1. In order to compute K_1 for use in the equation for $\bar{V}_m$, it will be necessary to assume a relationship between the hydraulic radius R and A_c. (See Equation (2-10) in Section 2 of DM-26.1). For relatively wide inlets, the hydraulic radius can be determined as follows:

$$R = A_c/\bar{w}_m \tag{2-11}$$

WHERE: R = hydraulic radius of inlet, in feet

A_c = cross-sectional area of inlet, in square feet

$\bar{w}_m$ = width of the inlet measured at mean sea level, in feet

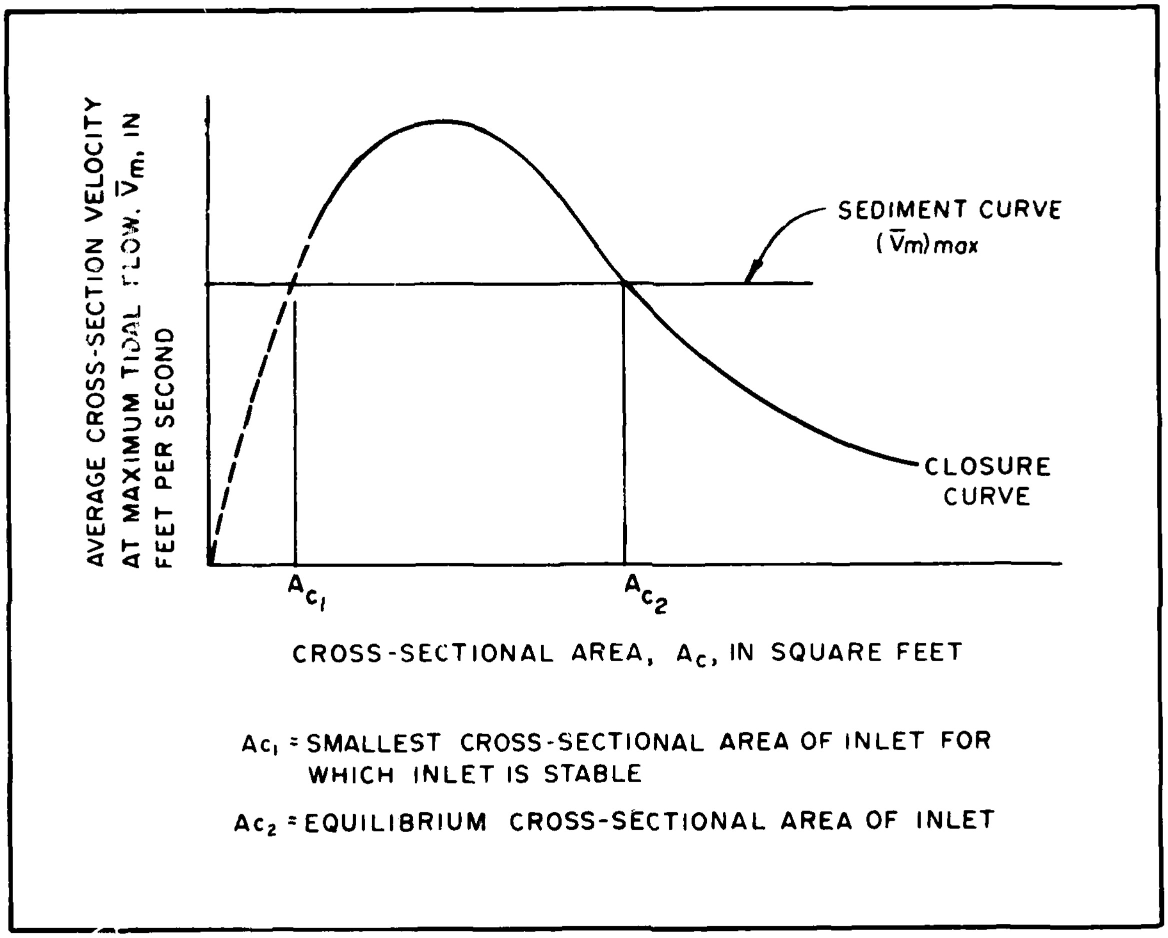


FIGURE 11
Inlet-Closure Curve

For small values of A_c, the closure curve is difficult to determine. This is due to the fact that the depth may be small and the possibility of sub-critical flow exists. However, for most practical purposes, it will be sufficient to compute the closure curve starting with values of A_c slightly smaller than the maximum value of A_c until A_{c1} is reached, and then sketch the remaining portion of the closure curve corresponding to smaller values of A_c

in by hand. The horizontal line in Figure 11 corresponds to the long-term equilibrium velocity, $(\bar{V}_m)_{max}$. This curve will be referred to as the sediment curve.

It follows from Figure 11 that for values of the cross-sectional area smaller than A_{c1} (corresponding to the first intersection of the closure curve and the sediment curve), tidal velocities are too small to maintain the cross section, and the inlet will shoal and ultimately close. For values larger than A_{c1} and smaller than A_{c2} (corresponding to the second intersection of the closure curve and the sediment curve), the tidal velocity is larger than the velocity required to maintain the cross-sectional area and the inlet cross section will scour until it reaches the value A_{c2}. Inlets with cross sections larger than A_{c2} will shoal until the cross-section reaches the value A_{c2}. Thus A_{c2} represents the long-term equilibrium cross-sectional area. The foregoing analysis implies that a condition for the inlet to remain open is that the closure and sediment curves intersect; that is, $\bar{V}_m \geq (\bar{V}_m)_{max}$.

The following equation permits a measure of the degree of stability of an inlet (whether or not the inlet will stay open):

$$P_R = [(A_{c2} - A_{c1})/A_{c2}][100] \qquad (2\text{-}12)$$

WHERE: P_R = percentage by which the inlet cross section can be reduced before the inlet will close

A_{c_2} = equilibrium cross-sectional area of inlet, in square feet

A_{c_1} = smallest cross-sectional area of the inlet for which inlet is stable, in square feet

For inlets with considerable longshore transport, it is recommended that P_R be larger than 0.5. For inlets with little longshore sediment transport, P_R can be smaller.

From the foregoing, certain inferences can be developed regarding the use of natural inlets as harbor entrances:

(1) When dredging a new inlet connecting a landlocked bay to the ocean, the dredged channel should have a cross section larger than A_{c1}.

(2) If existing natural channel depths are adequate for navigation, it may not be necessary to adjust the cross section at all, except to perhaps stabilize the inlet position with short jetties. If this is the case. a channel-bypass inlet will require continuous monitoring, and channel marker buoys may have to be shifted frequently to respond to natural channel migrations.

(3) Moderate deepening of a channel may be necessary for navigational purposes. Deepening can be achieved by increasing the cross-sectional area of the inlet. This change can be accomplished by increasing the bay water area and/or by improving the hydraulics of interior bay channels to make remote water areas contribute an

additional volume of water to the inlet system. This requires a change in the closure curve, as qualitatively shown in Figure 12. These modifications will increase the cross-sectional area of the inlet and deepen the channels where the channel-bypass mechanism predominates. However, these modifications may not be effective in an inlet where the bar-bypass mechanism predominates and where the critical depth is offshore and not in the inlet throat.

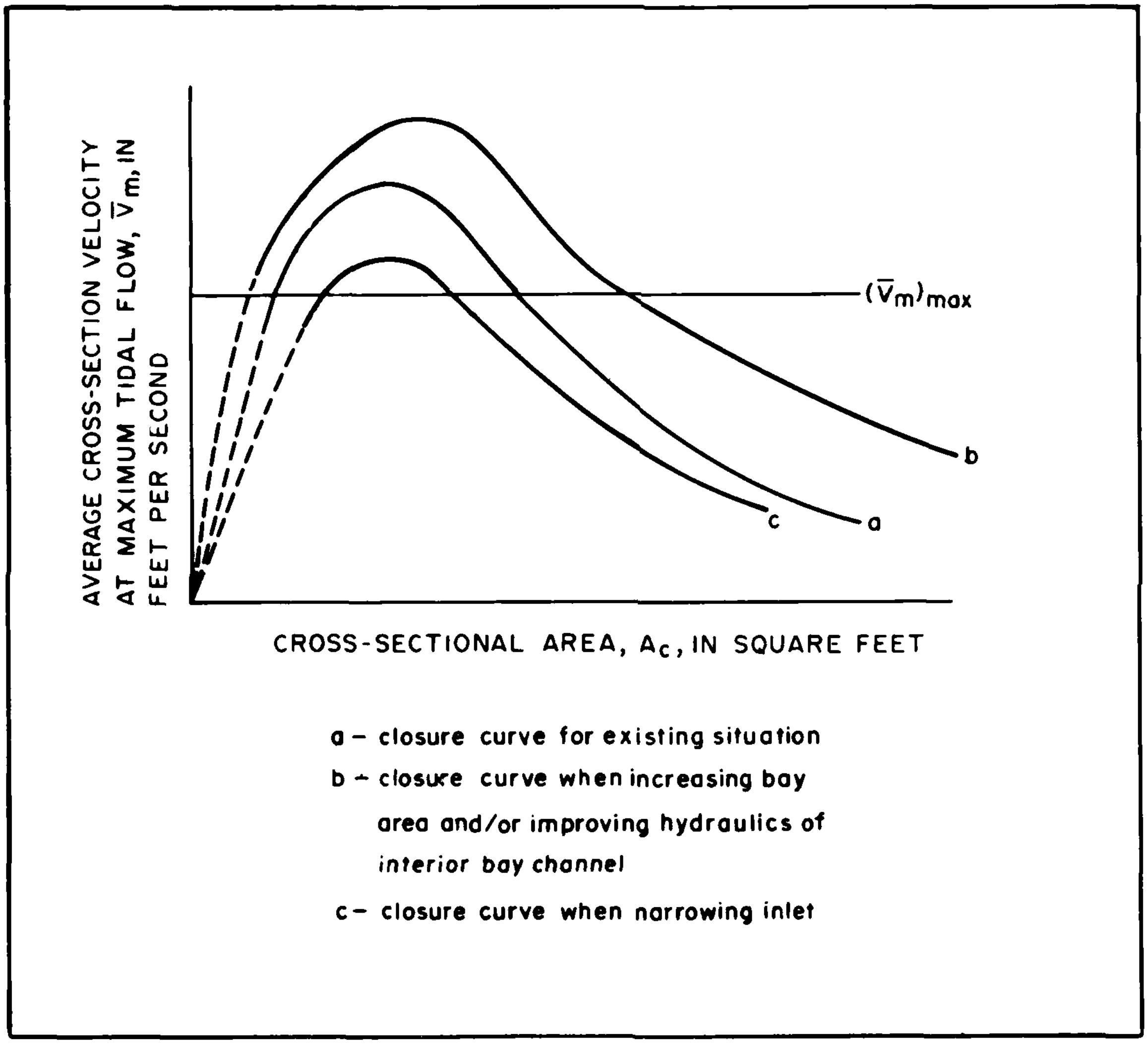


FIGURE 12
Changes in Closure Curve

(4) A tidal inlet can also be deepened by reducing its width. This technique can be quite sensitive to various aspects of the tidal hydraulics of the system. The result of decreasing the width of

the inlet is to shift the closure curve to become that labeled c in Figure 12, resulting in a smaller cross-sectional area. Whether this will lead to a larger depth in the inlet depends on whether A_c decreases faster than the width. Therefore, any design for major inlet-constriction works should be well-documented and verified with a physical model.

(5) Where significant deepening of a natural inlet is proposed, jetties are usually required, and entrance sedimentation considerations become similar to those for siting a harbor on an open sandy coastline.

d. Harbors in Estuaries. Harbors can be sited in estuaries. In many cases, there are problems associated with excess shoaling of the harbor with cohesive sediments. Cohesionless sediments may also be a factor; however, in general they are not a major factor unless the harbor is located in the vicinity of the ocean entrance to the estuary. A harbor located in an estuary, in contrast to one on an open coast, is generally subject to a different set of hydraulic and sedimentary conditions. The hydraulic regime is a result of complex interactions among the fresh-water discharge of the river, tidal currents, currents resulting from the difference in density between fresh water and sea water, and transverse currents resulting from two phenomena: reversing flows in curved sections of the estuary and Coriolis forces induced by the earth's rotation. Furthermore, wave action, either near the entrance to the estuary or in shallow areas of the estuary, may be an important factor. With regard to the sedimentary regime, sediment within an estuary can vary from cobbles to very fine colloidal materials in suspension. However, typical sediments reaching an estuary will consist of fine silts and clays carried in suspension.

(1) Classification of Estuaries. An estuary system is characterized as a semienclosed body of water having a free connection with the open sea and within which sea water is measurably diluted by fresh-water discharge of a river entering the bay. Estuaries can be classified by the degree of mixing between the fresh and salt water in terms of observed vertical salinity distribution. The classifications are given below:

(1) highly stratified;
(2) moderately stratified;
(3) well-mixed vertically, but with measurable lateral gradients; and
(4) well-mixed.

In general, the type of estuary system will go from (1) to (4) with decreasing river flow, increasing tidal velocities, increasing width, and decreasing depth. The classification of an estuary is related to the relative magnitude of fresh-water flow during a tidal cycle and the total amount of water that flows into and out of an estuary with the movement of the tide (tidal prism). The ratio of fresh-water flow per tidal cycle to the tidal prism is relatively large (greater than 1) for highly stratified cases and small (smaller than 0.1) for completely mixed cases. A highly stratified estuary will exhibit a well-defined interface or discontinuity in vertical salinity distribution. On the other hand, in a well-mixed estuary, the local salinity will vary a large amount vertically compared to the mean local salinity. In many cases, fresh-water flow quantities vary seasonally and can

produce highly stratified flow during flood runoff, whereas a moderately stratified or even well-mixed estuary may prevail during offpeak periods.

The hydraulics of a well-mixed estuary are generally similar to those involving a homogeneous fluid. However, the hydraulics of a highly stratified estuary are treated as though they involve a nonhomogeneous fluid. Figure 13 is a schematic of the interface between fresh water and salt water in a highly stratified estuary. This interface is referred to as an arrested salt-water wedge. The fresh-water discharge, being lighter than sea water, flows over the underlying salt-water wedge. Upstream movement of the wedge is arrested by the shear along the salt water-fresh water interface, which in turn returns a portion of the salt water downstream. This loss of salt water from the wedge is balanced by an upstream current within the salt-water body. The result is a system of strong, density-generated currents. In a constant-width channel, the fresh-water flow accelerates over the wedge, creating high surface velocities. Superposition of these density currents and tidal currents produces maximum ebb currents near the surface and maximum flood currents near the bed. The position of the interface varies with the tides, moving upstream with flood flow and downstream with ebb flow. An increase of fresh-water flow of the river will also move the interface downstream.

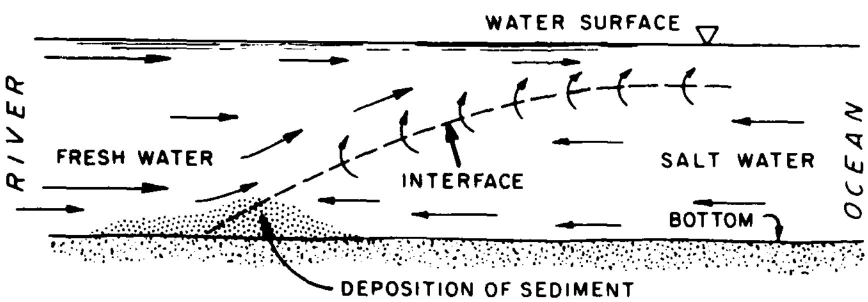


FIGURE 13
Schematic of Fresh Water-Salt Water
Interface in a Highly Stratified Estuary

(2) Sedimentation in Estuaries. Sediment carried by upland discharge of a river may vary from cobbles to colloids and may be transported as suspended or bed load. However, due to the lower velocities prevalent in most rivers as they enter estuaries, a large portion of the coarse sediment will settle out by the time the sediment reaches the toe of the salt-water wedge. Consequently, most sediment within an estuary consists of suspended silts and clays, and it is these particles which are transported back and forth with the flood and ebb currents of the tide. These sediments also create major shoaling problems in estuarine harbors. Currents in an estuary are produced by the tide, and, to a lesser degree, by the fresh-water discharge; therefore, both the currents and the fresh-water discharge are time-dependent. Consequently, the current-sediment system seldom reaches an equilibrium. Transportation of sediment from the bed, which in general consists of cohesive material, will only occur when the bed shear stress, which is related to tidal and fresh-water currents, is sufficient to entrain the material. Transportation of suspended sediments will vary according to the various states of turbulence present during a tidal cycle. Nevertheless, when considering a particular control volume, a net, or long-term, trend of erosion or deposition will occur. Deposition is the usual case.

In addition to the complex hydraulic and sediment phenomena present, the electrochemical properties of clay material add yet another complicating factor to the process. These electrochemical properties are such that, as the clay particles reach sufficient concentrations of salinity, a complex process takes place, which results in the ability of the particles to aggregate. Aggregation, also called flocculation, is the process whereby smaller particles adhere together to form larger particles, called flocs. These larger particles are more likely to settle; thus, the process of aggregation promotes shoaling of fine material in estuaries. The rate of aggregation increases as the amount of sediment in suspension increases. It also increases through turbulence, which increases the amount of interparticle collisions, to a point, after which further increase in turbulence will break up the relatively loose bond of the flocs.

If the bed shear stress is sufficiently low, as it is under low-velocity flow, these flocs, along with the fine silts, will deposit on the bottom. As they settle on the bottom, these cohesive sediments form interparticle bonds and consolidate with increasing overburden pressure. The greater the elapsed time and overburden, the more resistant the bed is to erosion. Determination of the critical bed shear stress to cause motion of these consolidated, cohesive bed forms is difficult.

When a harbor is placed in an estuary, it is often susceptible to shoaling. This results because the accompanying navigation channels, along with the supporting structures such as piers and breakwaters, often provide areas of low-velocity flow conditions where sediment may settle. Furthermore, the presence of the harbor, navigation channels, and supporting structures often modifies the flow conditions to the point where the estuary in the region of the harbor may shift to a stratified condition. This can be achieved by any measures which reduce the tidal flow or prism, any diversion of additional water into the estuary, or deepening and narrowing of the channel. Any shift towards a stratified condition will increase the amount of shoaling in the region of the harbor.

It is important to maintain adequate depths of a harbor to accomodate vessels using the harbor. (See DM-26.1.) The result is that, in many estuarine harbors, considerable maintenance dredging of shoaled material is required to ensure adequate depths in the harbor. This maintenance dredging is expensive and often may involve the dredging of quantities of up to 2,000,000 cubic yards per year. Therefore, it is desirable to design, or make modifications to, harbors such that adverse shoaling of cohesive sediments is minimized. This generally requires an investigation of the sediment characteristics, salinity distributions, and the hydraulic regime for the harbor. Krone and Einstein (1963) provide the following guidelines for procedures to minimize shoaling in estuarine harbors:

(1) Minimize the amount of suspended sediment entering a probable shoaling area. This can be achieved, to some degree, by preventing movements of tidal water containing suspended sediment from reaching a shoaling area through the use of dikes. It is also important to ensure that material dredged from shoaled areas is removed entirely from the estuary, if possible, as material dumped back into the water may return to the dredged area. This also can be achieved through the use of diked disposal sites; these are described in Section 3 of this manual.

(2) Minimize flow conditions which promote aggregation and low bed shear stress. The enlargement of channels generally reduces the bed shear stress. Unfortunately, it is usually necessary to enlarge natural channels in estuaries to provide safe navigation for vessels to be accomodated by a harbor. Maintenance of bed shear stress greater than the critical value required to initiate scour for most of the tidal cycle can be facilitated with the use of dikes. However, the economic feasibility of using these structures must be thoroughly investigated. This usually requires the use of physical-model studies. Flow conditions conducive to aggregation often occur in areas near piling and sudden enlargements of a channel. Where possible, smooth channel boundaries and gradual channel transitions, particularly those of the channel bottom, should be used. Parallel docking, with covered dock faces, may be used, where feasible, to provide minimum disturbance to flow. Where a salt-water wedge and clay sediment are present, shoaling is inevitable. The toe of the salt-water wedge may be moved by combining flows or by narrowing channels. In these ways, the location of shoaling may be moved to an area where maintenance dredging is more easily accomplished. A detailed investigation, including physical-model studies, is necessary to ensure the proper design of these types of modification.

(3) Minimize the amount of water containing suspended sediment that enters detached, off-channel harbor basins. This can be achieved by the use of a single, narrow opening. Such openings provide a minimum movement of water into and out of the basin during a tidal cycle. This method, however, may reduce water quality in the basin, which is generally not desirable.

Harbors sited in estuaries are generally susceptible to large amounts of

shoaled material. Detailed investigations are recommended to adequately minimize the adverse effects of this shoaling.

4. SHORE PROTECTION.

a. General. Where sediment-transport capacity exceeds sediment supply, shoreline erosion occurs. Shore-protection measures usually comprise either armoring the shoreline against further erosion or artificially preserving the beach. Fundamental to an understanding of littoral transport is the concept of the littoral cell, schematically illustrated in Figure 14. Sand is supplied from cliff erosion or from upland sources through river discharges. Most of this material is transported laterally along the beach and offshore by waves, where it is ultimately lost offshore in deep water. In addition, some material is lost inland by wind transport. Little of the material passes the downdrift headland. On other coastlines, this downdrift boundary could be an underwater canyon instead of a headland. Beach-preservation techniques may be implemented in the vicinity of the updrift side of the downdrift headland without inducing erosion of the beach downdrift of the headland. On the other hand, if protective measures are implemented elsewhere in the cell, the possibility of downdrift erosion should be investigated.

b. Shoreline Armoring. This method of shore protection involves the construction of seawalls or revetments. The structural design of these structures is discussed in DM-26.2. Because these structures are normally built in the surf zone, design wave heights are normally based on depth-limited breaking-wave conditions at storm-water levels or at extreme high tide. A major consideration in seawall design is the anticipated scour depth at the structure toe. The estimation of scour depth requires judgment. A steep foreshore slope fronting the structure requires little material removal to produce significant toe scour. A flat foreshore slope fronting the structure requires a significant quantity of material removal to produce toe scour. Vertical seawalls induce more toe scour than sloping revetments because of reflected wave energy. As mentioned in Subparagraph 3a (Littoral rocesses), the beach face is usually eroded by steep winter waves, and the andline is lowered. If a seawall is designed on the basis of a summer rvey, this phenomenon must be taken into account. The customary provision fo toe scour generally ranges from 2 to 4 feet below the winter sandline, depending on the type of structure, the relative coarseness of the beach material, and the foreshore slope. Long-term erosion effects must also be considered in the design of seawalls.

The designer needs to also consider failure modes (see DM-7) and repair possibilities in selecting design scour depths. A flexible rubble-mound revetment normally undergoes progressive failure, while a rigid seawall may fail suddenly when undermined. Where the wall is subject to periodic overtopping, care should be taken to provide adequate relief of pore pressure by providing weepholes through solid structures and an adequate filter material under porous revetments.

c. Beach Preservation. Where an eroding shoreline contains a beach or remnants thereof, it may be stabilized by preservation techniques. This can be accomplished either by increasing the material supply or by reducing beach losses. Reduction of losses can be achieved by creating downdrift barriers

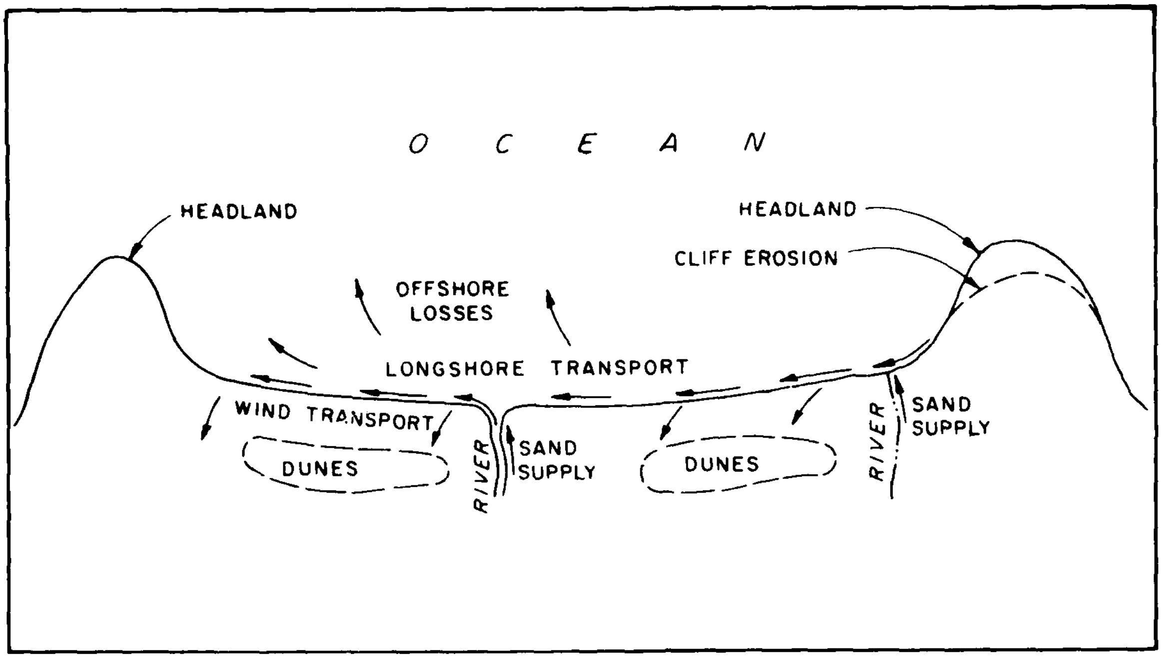


FIGURE 14
Littoral Cell (Closed Littoral System)

to arrest sand movement or by reducing the capacity of the mechanism that transports the sand through the reach. Beach-preservation techniques are presented below.

(1) Beach Nourishment. This method consists of direct placement of sand on the eroding beach from some outside source of sediment. This method supplements the natural supply of material to the reach of shoreline. The nourishment is usually carried out on a periodic basis. Where practical, it is desirable to place nourishment sand of equal or coarser grain size than that of the existing beach sand. Parameters controlling material loss to deep water due to winnowing (removal of fines) and offshore transport have been suggested by Krumbein and James (1965), James (1975), and Dean (1974); the relative winnowing-loss rate can be estimated through comparision of the grain-size distribution curves for both the borrow and the existing beach material. The material is generally distributed uniformly, in a width of approximately 50 feet, along the depleted shoreline beginning at the updrift end. Artificial beach nourishment has the advantage of supplying material to shorelines downcoast of the placement zone. This method is most effective where the transport rates are relatively low in comparison to the periodic renourishment quantity. Under these conditions, a single placement may sustain a beach for 5 or more years. The disadvantages of beach nourishment are few, but the possibility of filling up drainage pipes in the nearshore area exists.

(2) Beach-Loss Reduction Measures. As previously discussed, in Subparagraph 3a (Littoral Processes), the longshore-transport capacity is a function of the alongshore component of wave-energy flux; the main variables are wave height and breaker angle. The adjustment, or reduction, of these variable factors can result in the reduction of material loss, or may even induce accretion of material, along the affected coastline reach.

(a) Groins. Groins are commonly used as a means of beach preservation. The groin is a littoral barrier which reduces the amount of longshore transport by reducing the breaker angle. This is illustrated in Figures 15 through 18. In Figure 15, the shoreline configuration immediately after groin construction is shown. In time, material carried by longshore transport will be trapped against the groin in a fillet, as shown in Figure 16. The orientation of the fillet shoreline will be such that the angle between the breaking-wave crest and the fillet shoreline will be zero. However, because the groin is a littoral barrier, the downdrift side of the groin will be subject to erosion, as shown in Figure 17. In most cases, the downdrift erosion is alleviated through the placement of a groin field. If the groin field is properly constructed, the result will be a series of sand fillets on the updrift sides of the groins; with proper groin spacing, these fillets will achieve an equilibrium configuration that prevents erosion on the downdrift sides of the groins. (See Figure 18.)

Several factors must be taken into account to make a groin field effective. It must first be determined whether a dominant longshore component of wave-energy flux exists. If a dominant component does not exist, a groin field will not be effective. If it does exist, the dominant breaker angle must be determined. Groin length and groin spacing then become a function of this breaker angle and the beach profile.

In forming a littoral barrier, the shoreline of each fillet face moves seaward in an accretion profile until sand begins to move around the groin tips at the prevailing rate of longshore transport along the reach. If the groin head is in rather deep water, much of this material may be carried seaward by waves and lost offshore in deep water, thus aggravating downcoast erosion. Conversely, if the head is extended only into relatively shallow water, the littoral barrier is not effective in trapping material.

Groins appear to be most successful on a shoreline with a fairly steep foreshore slope that toes out on a flat or gently sloping offshore bottom, as illustrated in Figure 19. The profile of the foreshore accretion generally parallels the profile of the original foreshore, with the fillets accreting along the updrift side of the groin for an offshore distance approximately equal to the groin-tip extension beyond the slope inflection point. Where the inflection point occurs in relatively shallow water (to a depth less than twice the dominant breaker height), significant quantities of littoral material can pass the groin head, remaining in the longshore-transport zone to continue along to the downcoast beach. Conversely, where the underwater slope steepens with distance offshore, as shown in Figure 20, groins may move the sand off into deep water without creating an effective barrier.

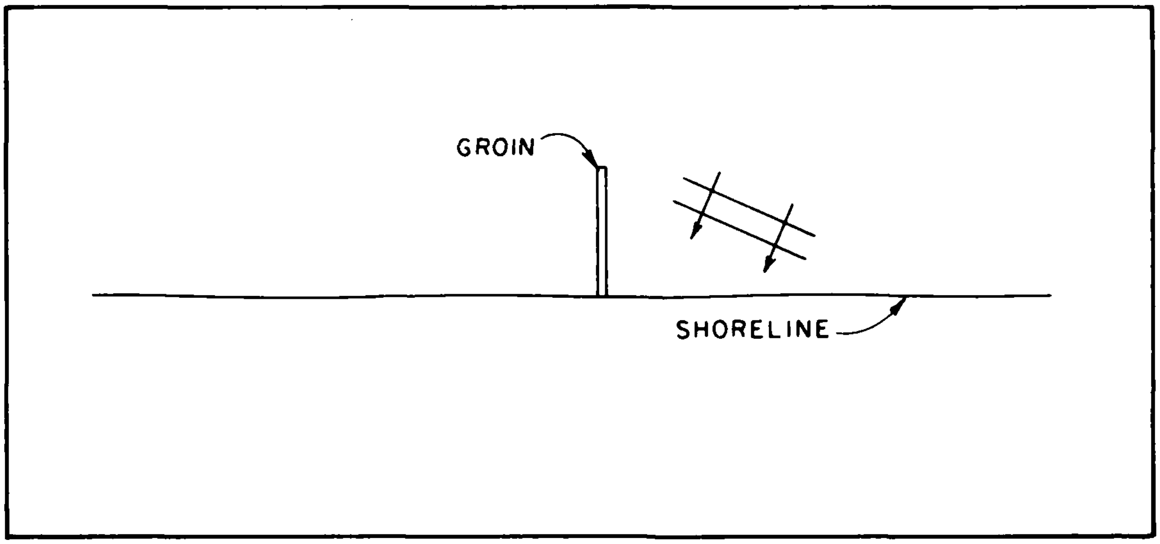


FIGURE 15
Groin Constructed Normal to Shoreline, Forming a Littoral Barrier

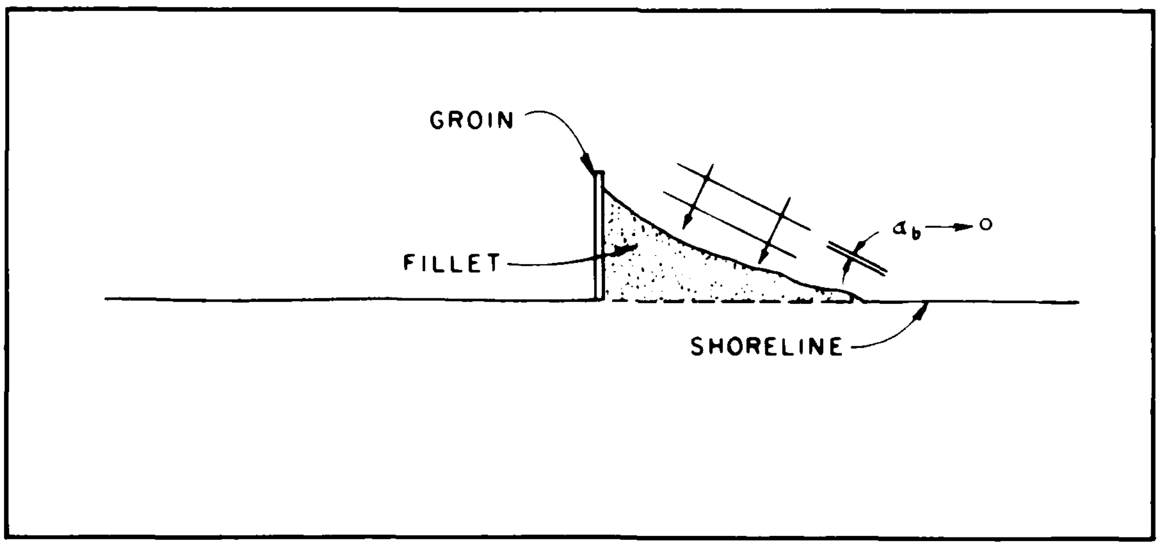


FIGURE 16
Updrift Fillet Face Alined With Breaker Angle Reduces Littoral Transport

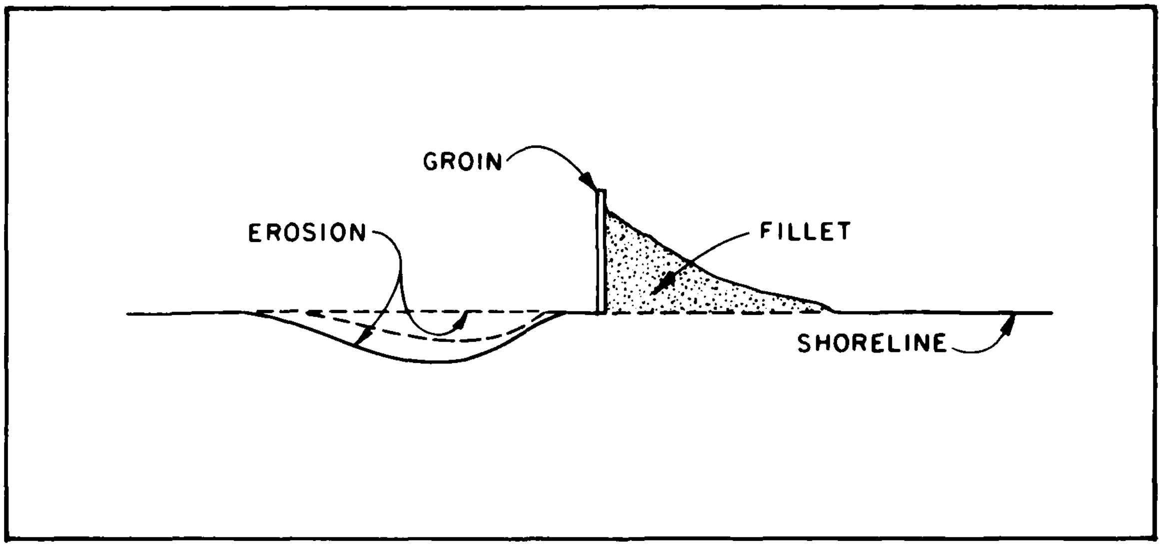


FIGURE 17
Unnourished Downdrift Beach Subject to Erosion

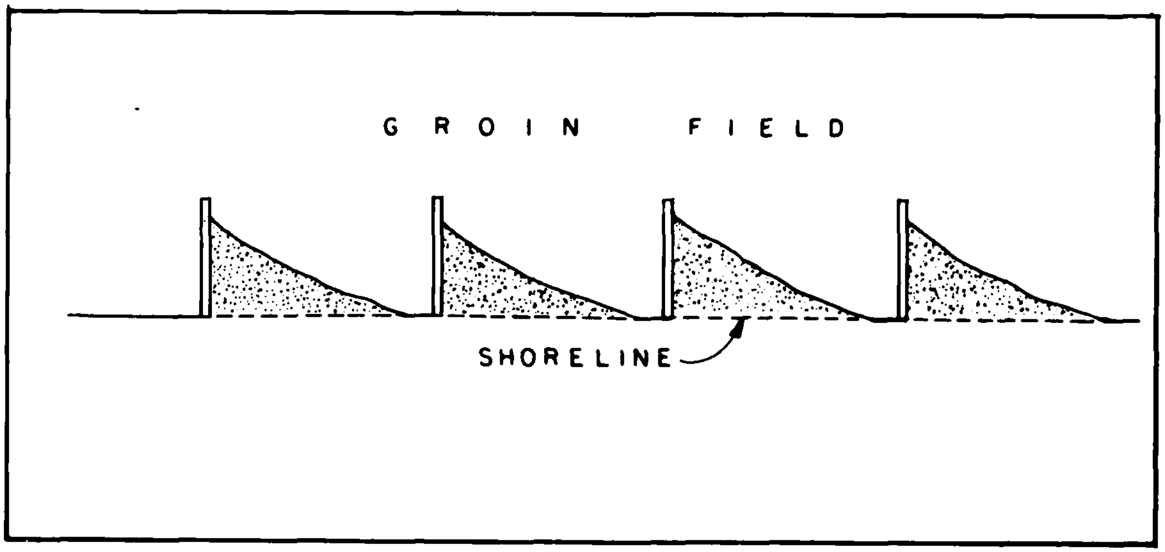


FIGURE 18
Groin Field

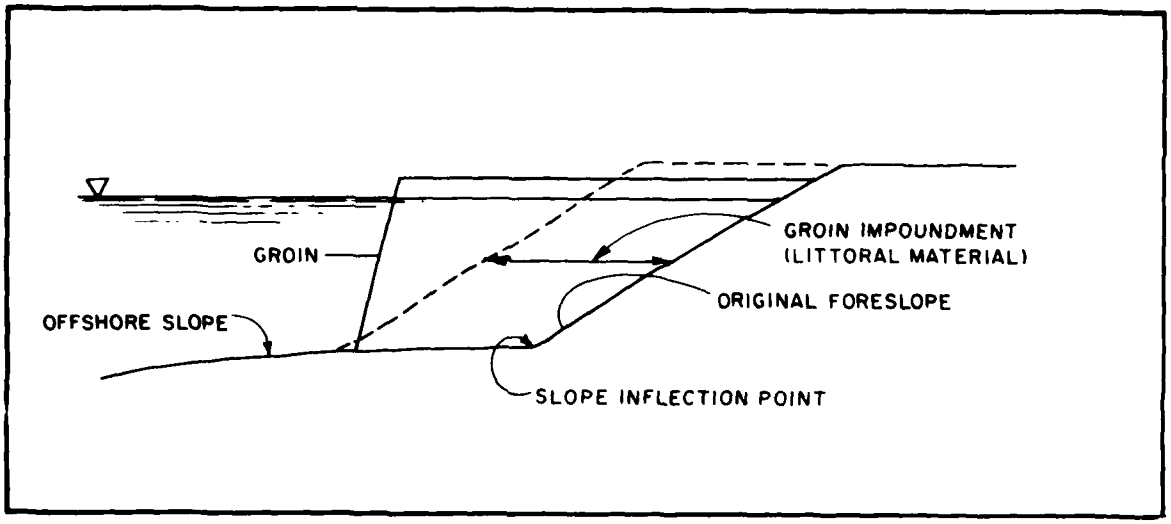


FIGURE 19
Groin Profile With Gently Sloping Offshore Bottom

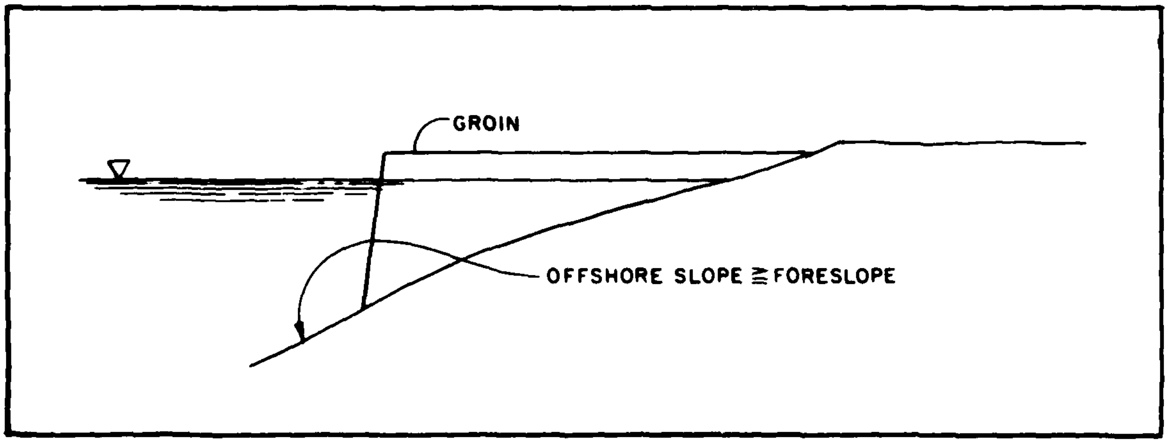


FIGURE 20
Groin Profile With Steepening Offshore Slope

Groin spacing is based on refraction analysis. (See DM-26.2.) By using refraction analysis, the designer should make sure that groin spacing will allow the shoreline configuration of the fillet to remain normal to the breaker direction as the fillet accretes on the updrift side of the groin. Where there exists one dominant wave direction, the refraction analysis will provide reliable results. Where there are several dominant wave directions, investigations should be made to ensure that the groins provide adequate littoral barriers when the direction of longshore transport changes.

Design of a groin field must include an investigation of the possibility of erosion downdrift of the field. If severe erosion downdrift will result, then it may be necessary to either extend the groin field downdrift or to use another means of shore protection. During construction, it is often desirable to fill the fillets with imported sand as part of the beach-preservation project.

(b) Offshore Breakwaters. Another method of beach preservation involves the placement of a detached breakwater system offshore in order to stabilize a reach of shoreline in its lee. The transport of sediment is diminished principally through the reduction of wave heights by the breakwaters and the realinement of wave-energy propagation. Figure 21 illustrates this method.

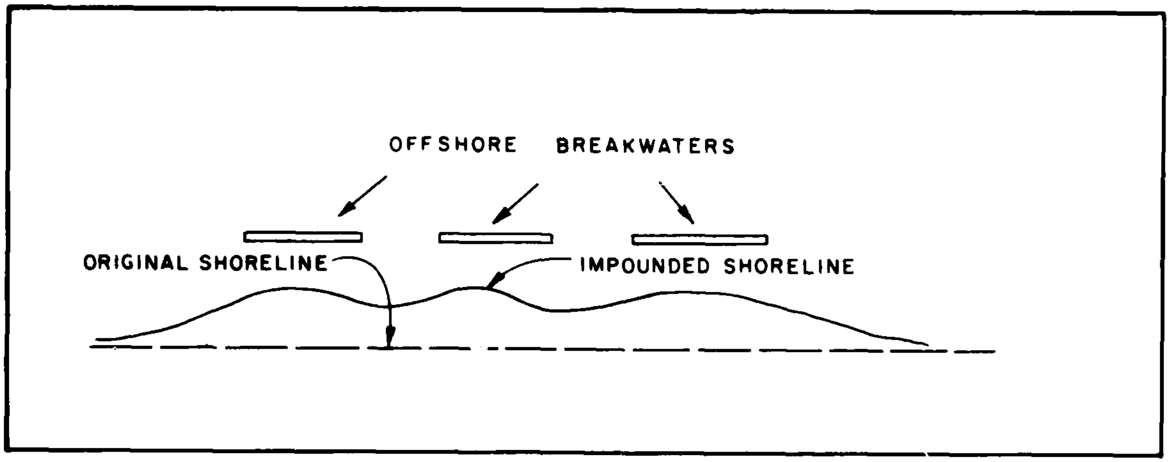


FIGURE 21
Beach Impoundment by Offshore Breakwaters

5. METRIC EQUIVALENCE CHART. The following metric equivalents were developed in accordance with ASTM E-621. These units are listed in the sequence in which they appear in the text of Section 2. Conversions are approximate.

32.2 feet per $second^2$	=	9.81 meters per $second^2$
1 square foot	=	0.09 square meter
1 cubic yard	=	0.76 cubic meter
3.3 feet per second	=	1 meter per second
2,000,000 cubic yards per year	=	1,530,000 cubic meters per year
2 feet	=	61.0 centimeters
4 feet	=	1.2 meters
50 feet	=	15.2 meters

Section 3. DREDGING

1. GENERAL. This section sets forth general criteria and procedural guidelines to use in dredging projects for harbors, turning basins, anchorage areas, and channels.

2. ACCOMPLISHMENT OF WORK.

a. Navy-Owned Equipment. Navy-owned dredges should be used to the maximum extent consistent with economy.

b. Corps of Engineers Equipment. When Navy-owned equipment suitable for the project is not available, the work may be accomplished by agreement with the Corps of Engineers, U.S. Army. (See NAVFAC P-68.)

c. Contracts with Private Firms. When the only suitable dredging equipment is in private ownership, or when the workload exceeds the capability of available government dredging facilities, dredging may be accomplished by private contractors.

3. CURRENT DREDGING PRACTICE. The dredging of naval harbors may involve the dredging of clay and silt from estuarine harbors or the dredging of sand from harbors on open coasts. By 1980, 87 percent of the Navy's total annual maintenance-dredging volume consisted of cohesive sediments, while 13 percent consisted of sand. Table 3 provides a list of harbors within the continental United States whose annual maintenance-dredging volumes exceed 100,000 cubic yards per year. A large part of the total dredging in naval harbors consists of removing shoaled material from under berthing piers. Other dredging activities include dredging of navigation channels and turning basins, as well as channel-entrance bypassing.

4. ECONOMIC FACTORS. The economic factors affecting the dredging of naval harbors are the following (Malloy, 1980):

a. Amount of Material to be Dredged. The mobilization and demobilization costs will constitute a significant portion of the total project cost for small-volume dredging projects. For large-volume dredging projects, the mobilization and demobilization costs will only increase the cost per cubic yard by a relatively small amount.

b. Distance From the Dredging Site to the Disposal Site. This distance depends on the availability of disposal sites, the volume, and the environmental quality of the dredged material. If the sediment is contaminated, regulatory agencies may require dumping at a "contained" land disposal site. In many areas these sites are limited. Ocean disposal sites are attractive alternatives because of their unlimited capacity and general proximity to Navy harbors. In either case additional costs and time delays may be incurred because the dredged material must be proven environmentally clean prior to issuance of a dredging permit. Regardless of where the material is dumped, cost is a function of distance to the disposal site and mode of transport.

TABLE 3

Listing of 12 Naval Harbors With Annual Maintenance-Dredging Averages and Sediment Types

Harbor	Average Annual Maintenance Dredging (million cubic yards)	Sediment Type
Mare Island Naval Shipyard	0.5	Mud
Alameda Naval Air Station	0.9	Mud
Molate Point Naval Fuel Depot	0.12	Mud
Port Hueneme Harbor	0.19	Sand
New London Naval Submarine Base	0.1	Mud
Naval Weapons Station Earle	0.2	Mud
Philadelphia Naval Shipyard	0.2	Mud
Norfolk Naval Station	0.38	Mud
Charleston Naval Base and Weapons Station	1.7	Mud
King's Bay Trident Base	2.0-2.2	70% Mud 30% Sand
Mayport Naval Station Basin	0.6	Mud
Port Canaveral	0.15	Sand

c. Environmental Considerations. Some form of environmental documentation is required for every dredging project and can add substantial costs. The minimum requirement is a Preliminary Environmental Assessment. Additional chemical or biological testing may be required to supplement this documentation. If ocean disposal is proposed, bioassays will probably be required at an additional cost. Most costly of all are environmental surveys of the dredge site and the disposal site which may be required in environmentally sensitive areas or cases of critical contamination.

d. New Work Versus Maintenance Dredging. Where an area has not been dredged before, the bottom sediments may be consolidated and difficult to dredge. The added time required to dredge new material may incur additional costs.

e. Other Factors. Other factors include the cost of fuel, competition between private and public dredgers, and the configuration and use of the naval harbor to be dredged.

5. PLANNING.

a. Jurisdiction and Permits.

(1) Jurisdiction. The U.S. Army Corps of Engineers has jurisdiction over construction and dredging in the navigable waters of the United States and of its territories and possessions. The U.S. Environmental Protection Agency (EPA) has jurisdiction over water quality relating to dredging, disposal of dredged material, and fill activities. Dredging activities and equipment must comply with U.S. Coast Guard regulations. Consultation with the district office of the U.S. Coast Guard is recommended before dredging projects are started.

(2) Permits.

(a) Federal permits. A Corps of Engineers permit is required to locate a structure, excavate, or discharge dredged or fill material in waters of the United States. A Corps of Engineers permit is also necessary for transport of dredged materials into ocean waters for the purpose of dumping. Application for Federal permits can be made through the local district office of the Corps of Engineers, U.S. Army. Applications must be accompanied by drawings of the dredge and disposal areas and a description of the proposed work. Although there are general guidelines established for the permit process, each district is somewhat autonomous and has the authority to amend the requirements for each particular project. These requirements include explanatory documentation of existing data, supplementary chemical and biological testing, and additional environmental surveys. The extent of each requirement is dependent upon the quantity and quality of the dredged material, the proposed form of disposal, and the environmental sensitivity of the area. To expedite permit application processing, cognizant regulatory agencies (Corps of Engineers/Environmental Protection Agency) should be contacted early in project planning. If environmental impact is assessed early, subsequent plans and alternatives can be guided by environmental considerations. In extreme cases, early notification can expedite processing emergency dredging permits by the Corps of Engineers.

(b) State permits. Federal law assures the right of any state or interstate agency to control the discharge of dredged or fill material in any portion of the navigable waters of any state jurisdiction. Typically, a water-quality certificate, a hydraulic-fill permit, or both, are required at the state level.

(c) Local permits. In certain areas, a local permit may be required.

b. Dredging-Site Investigations.

(1) Hydrographic Surveys. Proper planning cannot be accomplished without accurate hydrographic data. Factors affecting hydrographic surveys are given below.

(a) Horizontal control and adequate working charts. These must be available to provide accurate horizontal positioning for surveys and execution of work.

(b) Depth soundings. These can be accomplished by fathometer, leadline, or pole. The soundings should be reduced to the appropriate local low water datum.

(c) Tidal datum. Mean Low Water (MLW) and Mean Lower Low Water (MLLW) shall be used for soundings or depth measurements in all tidal waters as appropriate. Existing Corps of Engineers projects in rivers already have a specified datum. In areas outside the continental United States, the datum shall be that established for official use in the particular area involved.

(2) Sediment Analysis. Sediment samples from the dredge area should be obtained and analyzed.

(a) Grab samples. Samples for maintenance dredging are often not necessary as review of historical records reveals sediment characteristics. If samples are necessary for maintenance projects they are usually grab samples taken from the bed surface.

(b) Subsurface investigation. New-work dredging requires subsurface investigation. Recoverable cores are recommended where consolidated sediments may be encountered.

(c) Probing or sonar profiling. If rock pinnacles or debris are detected by grab or core samples, extensive probing or sonar profiling of the dredging area should be accomplished to locate and quantify rock and debris.

(d) Sediment testing. To evaluate dredging-plant requirements and disposal procedure, cohesionless samples should undergo mechanical sieve analysis. A chemical analysis is necessary for cohesive sediments. Bioassays may be necessary for cohesive sediments, depending on results of chemical analysis and proposed disposal action. If the project involves dredging of new sediments, a principal element of interest may be the density

(or consistency) of material and, for cohesive sediments, the shear strength. (Refer to DM-38 for test data.)

(3) Test Dredging. For very large new-work projects, consider test dredging in representative areas. This procedure is expensive due to mobilization and demobilization costs. As a result, this approach is seldom used.

(4) Environmental Analysis. Some form of environmental documentation is required as part of the permit process for all dredging projects. The extent of the documentation is determined by the quantity and quality of the sediment to be dredged and the proposed disposal methods. Chemical and biological testing may also be required, and in extreme cases, environmental surveys may be necessary. The material to be dredged must always be classified as polluted or unpolluted material.

(a) Dredging effects. If disposal effects are not an environmental concern, the effects of dredging can usually be evaluated with only a written document, particularly if there are some data available on the site and if the site is relatively uncontaminated. A significant amount of supplementary chemical and biological testing may be required, however, if the sediments are highly polluted. Field surveys of the dredge site may be necessary in cases of extreme environmental sensitivity or critical contamination.

(b) Disposal effects. Even if the potential impact of dredging can be evaluated with existing data and documentation, additional chemical and biological testing or field surveys may be required to evaluate the environmental impact of disposal. These evaluations can be even more extensive than those required for dredging effects. For example, if ocean dumping is proposed and there is a possibility that the sediment is contaminated, bioassays must be conducted according to rigid guidelines established in the Corps of Engineers/Environmental Protection Agency Implementation Manual. As with dredging, in cases of extreme environmental sensitivity or critical contamination, field surveys of the disposal site may be necessary in order to provide a complete evaluation of disposal effects.

c. Dredging Quantities. Dredging quantities are usually determined by the average-area method, using depths and locations on the hydrographic surveys. Accurate control of dredging is not possible. In some situations, it is less expensive to overdredge an area by 1 or 2 feet than to pay for the careful manipulation of dredging equipment and for the extra time involved in dredging to the exact depth required. Overdredging also allows for some additional shoaling before dredging is required again. Overdredging should be investigated for each specific site as it cannot be used in every situation.

d. Disposal Areas. Disposal locations are described as upland or in-water sites. The locations can be open or diked. Selection of an upland site requires consideration of return of effluent water to the waterway. Unnecessary entrapment of water that may cause flooding must be avoided. It must be assured that effluent water does not pick up additional turbidity or toxic chemicals as it returns to the waterway.

(1) Upland Open Site. This disposal location is generally used for placement of coarse, cohesionless sediments. Material placement is controlled with small berms constructed by a bulldozer or similar land-construction equipment.

(2) Upland Diked Site. This type of disposal location is generally used for the confined placement of fine-grained sediments. Dikes constructed prior to sediment placement typically have overflow weirs to minimize turbidity in receiving waters. Dikes may be constructed of existing soil or may be built up with hydraulically placed fill. Soil embankments should have a maximum slope of 1 vertical to 2 horizontal on the exterior face and 1 vertical to 3 horizontal on the interior face. Hydraulic fill must be placed at the natural angle of repose. Care should be taken to provide a cross-sectional area sufficient to withstand the water depths in the fill. A minimum freeboard of 2 feet is typical. Placement of dredged material at an upland diked site may cause ground-water contamination; investigations should be made to determine if this possibility exists. Certain situations require that the diked site be lined with filter cloth or a layer of clay to prevent penetration of pollutants into the ground-water system.

(3) Open-Water Site. With this type of disposal location, materials are generally limited to coarse sediments due to environmental considerations. EPA regulations and designated disposal areas should be investigated.

(4) *Contained-Water Site. For this type of disposal location,* earthen dikes are usually constructed prior to dredging. The use of silt curtains instead of earthen dikes is possible under certain combinations of sediment, tides, currents, and environmental considerations.

e. Use of Dredge Materials. Disposal of dredged material generally presents problems, particularly when there is a lack of candidate disposal sites. The beneficial use of dredged materials should be investigated. Common beneficial uses of dredge materials include the following:

(1) Landfill. Dredged sediments may be used as a landfill for commercial, industrial, and recreational purposes.

(2) Construction Materials. Coarse sediments are often suitable for use as construction aggregate. These sediments may be stockpiled for present and future use.

(3) Marshland Wetland Habitat. After intertidal- and submerged-fill operations are completed, shellfish larvae, wetland vegetation, or other organisms indigenous to the locale may be placed in the area to create a productive marshland.

(4) Upland Wildlife Habitat. During and after completion of above-water fills, seeding and contouring of sediments can provide a habitat indigenous to wildlife; this procedure may also prevent erosion.

(5) Beach Nourishment. Placement of suitable fill in water or on beaches can help to replenish losses of material caused by seasonal storms, washouts, currents, and other natural phenomena.

6. DREDGING EQUIPMENT.

a. Mechanical Dredges.

(1) Description. Mechanical dredges dislodge and raise sediment by mechanical means. Mechanical-dredging methods are generally used in protected waters, but because the equipment is relatively mobile, some mechanical dredging may be accomplished in open water during short-term, calm-water conditions. Mechanically dredged sediments may be disposed alongside the dredge at a dumpsite or may be transferred to scows which transport the sediments to a dump site. The production rate by means of mechanical dredging is relatively low.

(2) Types.

(a) Clamshell, grab, or bucket dredge. This system consists of a crane, or derrick, mounted on a floating barge, with a clamshell, orangepeel, or dragline bucket used to pick up sediment and transfer it to an adjacent scow or barge. This dredge may be a specially built machine or may consist of land equipment on a suitable floating platform. This form of dredging can remove loose, unconsolidated sediments ranging in size from silts and clays to blasted rock. The dredge can be used in moderate-swell conditions. The system is not exceedingly efficient but has the advantage of high mobility. This mobility enables dredging at the base of bulkheads, piers, and fender piles without damaging these structures or the dredge equipment.

(b) Ladder, or bucket-ladder, dredge. This dredge consists of a floating dredge that has a continuous chain of buckets on a frame which is called a ladder. Each of the buckets possesses a cutting edge for digging into the sediment. The ladder is lowered to the bed so that the buckets can reach and cut sediments to be dredged. The buckets dump the dredged sediment by gravity at the opposite end of the ladder onto a conveyor system or an adjacent open barge. The barge may then transport the material to the disposal site. This dredging system is effective in hardpan and cemented sediments, but is ineffective in firm rock. The system cannot be used in swell conditions. This system is not often used in the United States.

(c) Dipper-barge dredge. This dredge consists of a backhoe mounted on a barge equipped with a trapdoor shovel. Sediment is removed from the bed and deposited alongside the dredge, in another barge, in the water, or onshore. Where the sediment is deposited depends on the length of backhoe reach. Spuds, which penetrate the bottom, are usually used to keep the barge from moving during a dredging activity. This dredging method is effective for hardpan and cemented sediments, as well as for firm rock that has been blasted. The effectiveness of this type of dredging system is limited in moderate-swell conditions.

b. Hydraulic Dredges.

(1) Description. Hydraulic dredges lift sediment from the bottom and transport it by means of a centrifugal pump. Hydraulic dredges can be used in either open or protected waters, depending on the type of dredge.

The dredged material is transported in a slurry and is generally discharged by a pipeline in the hull of the dredge; the slurry is discharged alongside the dredge, or it may be pumped ashore. The rate of production depends on sediment type, depth of cut, and dredge size and power; it generally exceeds that of mechanical dredges.

(2) Types.

(a) Pipeline, or suction, dredge. This dredge consists of a barge-mounted centrifugal pump. A suction line, or pipe, extends from the pump beyond the bow and is lowered to the bed by means of an "A" frame and ladder. At the end of this ladder, the pipe moves along the bottom dislodging the material. The material is then pumped in a slurry to a discharge line extending beyond the stern of the dredge. The material may then be pumped to the disposal site through a discharge line. The distance through which the material may be pumped can be extended by using booster pumps. Sweeping the suction pipe over an area at constant depth will result in the excavation of the channel bottom. Pipeline dredges are not self-propelled, but move by forward-mounted swing wires and aft-mounted walking spuds or wires. This type of dredge can be operated safely only in the absence of moderate to high swell; it can excavate material ranging from clays and silts to blasted rocks. The dredge is generally capable of dredging large volumes of material. Pipeline dredges are usually limited to excavation depths of approximately 60 feet. The rate of production will decrease with increased length of discharge line, increased lift, and increased bed-sediment compaction.

(b) Cutterhead dredge. This dredge consists of a pipeline dredge equipped with a rotary cutter at the end of the ladder. The cutter is used to dislodge bed sediments.

(c) Dustpan dredge. This dredge consists of a pipeline dredge with a dustpan-shaped head at the end of the ladder. The head is equipped with water jets which are used to dislodge bed sediments.

(d) Bucket-wheel excavator. This dredge consists of a pipeline dredge with a bucket wheel rotating (on a horizontal axis) at end of the ladder.

(e) Trailing suction dredge. This dredge consists of a self-propelled or tug-assisted vessel. The hull of the vessel contains a hopper and the dredge is equipped with one or two suction pipes (normally fitted with drag heads) extending below the hull to the bed. This dredge usually operates while underway, drawing slurry by centrifugal pumps to the hopper, where excess water is overflowed back to the waterway. Sediment is discharged at the disposal site by opening doors located on the hopper bottom or by pumping out the hopper. This dredge is a self-contained unit and is capable of operating in higher swell conditions. Because the dredge is self-propelled, it is capable of dredging material from sites which are large distances from the point of disposal.

(f) Hopper dredge. This dredge consists of a trailing suction dredge with a ship-shaped hull, a bridge, an engine room, and crew quarters.

This dredge is typically used for the dredging of estuary and river-mouth bars that are prone to ocean-swell conditions.

c. Special Equipment.

(1) High Solids-Content Dredge. This dredge consists of a floating system capable of pumping high concentrations of solids through the use of compressed air. It is primarily used for removal of industrial wastes from rivers and harbors. The production rates are generally low and the distance over which the material may be pumped is limited. This type of dredge is not generally available.

(2) Elevated-Platform Dredge. This system consists of a pipeline dredge that incorporates a "jack-up" barge to elevate the equipment above the surface swells. The system incorporates a submerged discharge pipeline. Availability of this type of dredge is very limited.

d. Selection of Dredging Equipment. Principal considerations upon which equipment selection is made include:

(1) exposure of dredging site;
(2) volume and distribution of materials to be dredged;
(3) type of material to be dredged;
(4) location of disposal area;
(5) distance to disposal area;
(6) time available for work;
(7) vessel traffic; and
(8) availability of equipment.

7. METRIC EQUIVALENCE CHART. The following metric equivalents were developed in accordance with ASTM E-621. These units are listed in the sequence in which they appear in the text of Section 3. Conversions are approximate.

100,000 cubic yards = 76,500 cubic meters
1 foot = 30.5 centimeters
2 feet = 61.0 centimeters
60 feet = 18.3 meters

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DM-5	Civil Engineering
DM-5.8	Pollution Control Systems
DM-6	Drawings and Specifications
DM-7	Soil Mechanics, Foundations, and Earth Structures
DM-26.1	Harbors
DM-26.2	Coastal Protection
DM-38	Weight Handling Equipment and Service Craft

GLOSSARY

Accretion. May be either natural or artificial. Natural accretion is the buildup of land, solely by the action of the forces of nature, on a beach by deposition of waterborne or airborne material. Artificial accretion is a similar buildup of land by reason of an act of man, such as the accretion formed by a groin, breakwater, or beach fill deposited by mechanical means.

Aggregate. A group or mass of distinct things gathered together.

Aggregation. The formation of aggregates resulting from the successive collisions of suspended cohesive particles. (See Flocculation.)

Alongshore. Parallel to and near the shoreline; same as Longshore.

Angle of Repose. The natural angle (from the horizontal) that a cohesionless soil will assume as it piles up when, for example, poured from a funnel.

Bar. A submerged or emerged embankment of sand, gravel, or other unconsolidated material built on the sea floor in shallow water by waves and currents.

Barge. An unpowered vessel used for transporting freight.

Bay. A recess in the shore or an inlet of a sea between two capes or headlands, not as large as a gulf but larger than a cove.

Beach. The zone of unconsolidated material that extends landward from the low water line to the place where there is marked change in material or physiographic form, or to the line of permanent vegetation (usually the effective limit of storm waves). The seaward limit of a beach--unless otherwise specified--is the mean low water line. A beach includes Foreshore and Backshore.

Bed. The bottom of a body of water.

Bedload. (See Load.)

Bed Shear Stress. The force per unit area exerted, in the direction of flow, on the bottom by the water flow present.

Berm. A nearly horizontal part of the beach or backshore formed by the deposit of material by wave action. Some beaches have no berms, others have one or several.

Breaker. A wave breaking, such as on a shore or over a reef.

Breakwater. A structure protecting a shore area, harbor, anchorage, or basin from waves.

Bulkhead. A structure, designed to retain earth, which consists of a vertical wall sometimes supplemented by an anchor system.

Bypassing, Sand. Hydraulic or mechanical movement of sand from the accreting updrift side to the eroding downdrift side of an inlet or harbor entrance. The hydraulic movement may include natural movement as well as movement caused by man.

Canal. An artificial watercourse cut through a land area for such uses as navigation and irrigation.

Canyon. A relatively narrow, deep depression with steep slopes, the bottom of which grades continuously downward. May be underwater (submarine) or on land (subaerial).

Celerity, Wave. Wave speed.

Centrifugal Pump. A pump operated by centrifugal force, the force outward exerted by a body moving in a curved path.

Channel. (1) A natural or artificial waterway of perceptible extent which either periodically or continuously contains moving water, or which forms a connecting link between two bodies of water. (2) The part of a body of water deep enough to be used for navigation through an area otherwise too shallow for navigation. (3) The deepest part of a stream, bay, or strait through which the main volume or current of water flows.

Chart Datum. The plane or level to which soundings (or elevations) or tide heights are referenced (usually Low Water Datum). The surface is called a Tidal Datum when referred to a certain phase of tide. To provide a safety factor for navigation, some level lower than Mean Sea Level, such as Mean Low Water or Mean Lower Low Water, is generally selected for hydrographic charts.

Clamshell. A dredging bucket made of two similar pieces hinged together at one end.

Cliff. A high, steep face of consolidated material or rock.

Coast. A strip of land of indefinite width (may be several miles) that extends from the shoreline inland to the first major change in terrain features.

Cohesionless Soils. Soils or sediments which do not exhibit cohesion.

Cohesive Soils. Soils or sediments which tend to stick together as parts of the same mass.

Colloid. A substance made up of very small, insoluble, nondiffusible particles, larger than most inorganic molecules but small enough so that they remain suspended in a fluid medium without settling to the bottom.

Contour. A line on a map or chart representing points of equal elevation with relation to a Datum.

Core. A vertical cylindrical sample of the bottom sediments from which the nature and stratification of the bottom may be determined.

Coriolis Force. A fictitious force used mathematically to describe motion relative to a noninertial, uniformly rotating frame of reference, such as the earth.

Current. A flow of water.

Datum Plane. The horizontal plane to which soundings, ground elevations, or water-surface elevations are referred. The plane is called a Tidal Datum when defined by a certain phase of the tide.

Deep Water. Water so deep that surface waves are little affected by the ocean bottom. Generally, water deeper than one-half the surface wavelength is considered deep water.

Delta. An alluvial deposit, roughly triangular or digitate in shape, formed at a river mouth.

Density Current. A current resulting from the differences in density within a water mass.

Depth of Breaking. The stillwater depth at the point where the wave breaks.

Dike. A wall or mound built around a low-lying area to prevent flooding.

Downdrift. The direction of predominant movement of littoral materials.

Drag Head. A device placed on the end of a suction pipe (connected to a dredge) used for loosening or cutting away the bottom material that is to be dredged.

Dunes. Ridges or mounds of loose, windblown material, usually sand.

Ebb Current. The tidal current away from shore or down a tidal stream; usually associated with the decrease in the height of the tide.

Ebb Tide. The period of tide between high water and the succeeding low water; a falling tide.

Erosion. The wearing away of land by the action of natural forces. On a beach, the carrying away of beach material by wave action, tidal currents, littoral currents, or by deflation (wind transport).

Estuarine. (1) Formed in an estuary. (2) Found in estuaries.

Estuary. (1) The part of a river that is affected by tides. (2) The region near a river mouth in which the fresh water of the river mixes with the salt water of the sea.

Fathometer. The copyrighted trademark for a type of echo sounder.

Fender Pile. A pile used to take the impact of a berthing or berthed vessel.

Fillet. The accumulation of littoral material adjacent to a coastal structure such as a groin or a jetty.

Flocculation. The process of forming aggregated or compound masses of particles. (See Aggregation.)

Floc. A bit of flocculent matter in a liquid.

Flood Current. The tidal current toward shore or up a tidal stream, usually associated with the increase in the height of the tide.

Flood Tide. The period of tide between low water and the succeeding high water; a rising tide.

Fluvial. Of, pertaining to, or produced by a river.

Foreshore. The part of the shore, lying between the crest of the seaward berm (or upper limit of wave wash at high tide) and the ordinary low water mark, that is ordinarily traversed by the uprush and backrush of the waves as the tides rise and fall.

Freeboard. (1) The additional height of a structure above design high water level to prevent overflow. (2) At a given time, the vertical distance between the water level and the top of the structure.

Groin. A shore-protection structure built (usually perpendicular to the shoreline) to trap littoral drift or retard erosion of the shore.

Groin Field. A series of groins acting together to protect a section of beach.

Group Velocity. The velocity of a wave group. In deep water, it is equal to one-half the velocity of the individual waves within the group. In shallow water, it is equal to the phase velocity of each individual wave.

Harbor. In general, a sheltered arm of the sea, bounded by natural features, manmade structures, or a combination of both, in which ships may seek refuge, transfer cargo, and/or undergo repair.

Hardpan. (1) Any layer of firm detrital matter, as of clay, underlying soft soil. (2) Hard, unbroken ground.

Headland. A high, steep-faced promontory extending into the sea.

Hopper. A funnel-shaped chamber in which materials are stored temporarily and later discharged through the bottom.

Hydraulic Radius. The ratio of the water area to its wetted perimeter.

Inlet. A short, narrow waterway connecting a bay, lagoon, or similar body of water with a large parent body of water.

Intertidal. Refers to the land area that is alternately inundated and uncovered with the tides, usually considered to extend from mean low water to extreme high tide.

Jetty. On open seacoasts, a structure extending into a body of water, designed to prevent shoaling of a channel by littoral material and to direct and confine the stream or tidal flow. At the mouth of a river or tidal inlet, jetties are built to help maintain and stabilize a channel.

Leadline. A line, wire, or cord used in sounding. It is weighted at one end with a plummet.

Littoral. Of or pertaining to a shore, especially of the sea.

Littoral Current. Any current in the littoral zone caused primarily by wave action. Examples are Longshore Current and Rip Current.

Littoral Drift. The sedimentary material moved in the littoral zone under the influence of waves and currents.

Littoral Transport. The movement of littoral drift in the littoral zone by waves and currents. Includes movement parallel (Longshore Transport) and perpendicular (Onshore/Offshore Transport) to the shore.

Littoral Transport Rate. Rate of transport of sedimentary material parallel to or perpendicular to the shore in the littoral zone. Usually expressed in cubic yards (meters) per year. Commonly used synonymously with Longshore Transport Rate.

Littoral Zone. In beach terminology, an indefinite zone extending seaward from the shoreline to just beyond the breaker zone.

Load. The quantity of sediment transported by a current. It includes the Suspended Load of small particles and the Bedload of large particles that move along the bottom.

Longshore. Parallel to and near the shoreline. Same as Alongshore.

Longshore Current. The littoral current in the breaker zone moving essentially parallel to the shore, usually generated by waves breaking at an angle to the shoreline.

Longshore Transport. The movement of littoral drift parallel to the shore by waves and currents.

Longshore Transport Potential. The potential rate at which a given set of hydraulic conditions would transport sedimentary material along the shore.

Longshore Transport Rate. Rate of transport of sedimentary material parallel to the shore. Usually expressed in cubic yards (meters) per year. Commonly used synonymously with Littoral Transport Rate.

Mean Lower Low Water (MLLW). The average height of the lower low waters over a 19-year period. For shorter periods of observations, corrections are applied to eliminate known variations and reduce the results to the equivalent of a mean 19-year value.

Mean Low Water (MLW). The average height of the low waters over a 19-year period. For shorter periods of observations, corrections are applied to eliminate known variations and reduce and results to the equivalent of a mean 19-year value.

Mean Sea Level. The average height of the surface of the sea for all stages of the tide over a 19-year period, usually determined from hourly height readings. Not necessarily equal to Mean Tide Level.

Median Diameter. The diameter which marks the division of a given sand sample into two equal parts by weight, one part containing all grains larger than that diameter and the other part containing all grains smaller.

Nourishment. The process of replenishing a beach. It may be brought about naturally, by Longshore Transport, or artificially, by the deposition of dredged materials.

Offshore. A direction seaward from the shore.

Offshore Current. (1) Any current in the offshore zone. (2) Any current flowing away from shore.

Offshore Transport. The movement of littoral drift offshore by waves and currents.

Onshore. A direction landward from the sea.

Onshore Transport. The movement of littoral drift onshore by waves and currents.

Phase. In surface wave motion, a point in the period to which the wave motion has advanced with respect to a given initial reference point.

Phase Velocity. Propagation velocity of an individual wave as opposed to the velocity of a wave group.

Phi Grade Scale. A logarithmic transformation of the Wentworth Scale for size classifications of sediment grains based on the negative logarithm to the base 2 of the grain diameter, d: $\phi = -\log_2 d$. (See Soil Classification.)

Pore Pressure. The pressure exerted by the water contained in the spaces between individual soil particles which acts either on the particles themselves or on structural elements embedded in, or adjacent to, the soil.

Profile, Beach. The intersection of the ground surface with a vertical plane; may extend from the top of the dune line to the seaward limit of sand movement.

Refraction (of Water Waves). The process by which the direction of a wave moving in shallow water at an angle to the contours is changed. The part of the wave advancing in shallower water moves more slowly than that part still advancing in deeper water, causing the wave crest to bend toward alinement with the underwater contours.

Refraction Diagram. A drawing showing positions of wave crests and/or orthogonals in a given area for a specific deepwater wave period and direction. (An orthogonal is a line drawn perpendicularly to the wave crests.)

Revetment. A facing built to protect a scarp, embankment, or shore structure against erosion by wave action or currents.

Salinity. Measure of the quantity of total dissolved solids in water. Salinity is usually expressed as total weight, in grams, of salts dissolved in one kilogram of sea water and written 0/00 (parts per thousand).

Scour. Removal of underwater material by waves and currents, especially at the base or toe of a shore structure.

Scow. A large, flat-bottomed, unpowered vessel used chiefly for freight, such as mud or coal; a low-grade lighter or barge.

Seas. Waves caused by wind at the place and time of observation. (See Swell.)

Seawall. A structure separating land and water areas, primarily designed to prevent erosion and other damage due to wave action.

Sedimentation. The deposition or accumulation of sediment.

Sediment Transport. The movement of sedimentary material.

Shallow Water. Commonly, water of such a depth that surface waves are noticeably affected by bottom topography. It is customary to consider water of depths less than one-half the surface wavelength as shallow water.

Shoal. (1) (Verb) (a) To become shallow gradually. (b) To cause to become shallow. (c) To proceed from a greater to a lesser depth of water. (2) (Noun) A rise of the sea bottom due to an accumulation of sand or other sediments.

Sink. Any process that decreases the quantity of sediment in a control volume.

Slurry. A viscous mixture of soil and water.

Soil Classification. An arbitrary division of a continuous scale of grain sizes such that each scale unit or grade may serve as a convenient class interval for conducting an analysis or for expressing the results of an analysis. There are many classifications used; the two most often used are the Wentworth Scale and the Unified Soil Classification. (See Table 1 of text.)

Source. Any process that increases the quantity of sediment in a control volume.

Spring Tide. A tide that occurs at or near the time of new of full moon (syzygy) and which rises highest and falls lowest from the mean sea level.

Spud. A column, extending down from a dredge, used for maneuvering in water.

Stream. A current in the sea formed by, for example, wind action or water density differences.

Surf Zone. The area between the outermost breaker and the limit of wave uprush.

Suspended Load. The material moving in suspension in a fluid, being kept up by the upward components of the turbulent currents or by colloidal suspension. (See Load.)

Swell. Wind-generated waves that have traveled out of their generating area. Swell characteristically exhibit a more regular and longer period, and have flatter crests, than waves within their fetch. (See Seas.)

Tidal Current. The alternating horizontal movement of water associated with the rise and fall of the tide caused by the astronomical tide-producing forces.

Tidal Inlet. (1) A natural inlet maintained by tidal flow. (2) Loosely, any inlet in which the tide ebbs and flows. (See Inlet.)

Tidal Prism. The total amount of water that flows into a harbor or estuary or out again with movement of the tide, excluding any fresh-water flow.

Tide. The periodic rising and falling of the water that results from gravitational attraction of the moon and sun and other astronomical bodies acting upon the rotating earth. Although the accompanying horizontal movement of the water resulting from the same cause is also sometimes called the tide, it is preferable to designate the latter as Tidal Current, reserving the name Tide for the vertical movement.

Turbidity. Quality or state of being turbid. Water which contains suspended matter which interferes with the passage of light through the water or in which visual depth is restricted is referred to as Turbid.

Updrift. The direction opposite that of the predominant movement of littoral materials.

Viscosity. That molecular property of a fluid that enables it to support tangential stresses for a finite time and thus to resist deformation.

Void Ratio. The ratio of the volume of voids to the volume of solids.

Wave Crest. (1) The highest part of a wave. (2) That part of the wave above stillwater level.

Wave-Energy Flux. The total amount of wave energy delivered to a given shore segment over a season or year, broken down by direction. The longshore component of the flux on either side of the normal-to-shore is indicative of the gross potential rate of longshore transport in the component direction. The difference between components in each direction is indicative of the net potential longshore transport rate in the predominant direction.

Wave Group. A series of waves in which the wave direction, wavelength, and wave height vary only slightly.

Wave Height. The vertical distance between a crest and the preceding trough.

Wavelength. The horizontal distance between similar points on two successive waves measured perpendicularly to the crest.

Wave Period. The time for a wave crest to traverse a distance equal to one wavelength. The time for two successive wave crests to pass a fixed point.

Weephole. A drainage or pressure-relief opening in an otherwise watertight structure.

Weir. An obstruction placed across a stream, thereby causing the water to pass through a particular opening or notch.

Weir Jetty. An updrift jetty with a low section or weir over which littoral drift moves into a predredged deposition basin which is dredged periodically.

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